A Comparative Framework for Building Life Cycle Embodied Carbon Emissions Databases and Its Application for Public Databases

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Abstract

Data availability and accuracy are some of the main obstacles to calculating the life-cycle embodied carbon emissions in buildings. There have been several studies to assess life cycle assessment (LCA) databases in the past. These database studies often rely heavily on commercial databases, and most studies only evaluate a single data point for each material in the building life cycle inventory. Comparing databases in this manner can be potentially biased, not representative as a whole, and lacking a systematic approach. This study proposes a systematic comparative framework as an addition to existing methods to aid the comparison of construction-material embodied carbon databases, which comprise a part of LCA. The framework identifies the underlying issues and difficulties in comparing embodied carbon databases. It then provides a fair method for data comparison across the databases. Finally, it assists the understanding of data availability and data homogeneity within and across the databases. The framework's applicability is demonstrated by comparing three publicly available databases: EC3, the ICE Database, and the ÖKOBAUDAT Database. Life cycle embodied carbon assessments (LCECA) on a single-family house are performed using the aggregate data from the three public databases and the commercial database Gabi Database within the LCA tool Tally. The embodied carbon study suggests that the materials' median embodied carbon factors value from the aggregated public database provides a reasonable embodied carbon assessment compared to the commercial data. However, the heterogeneity of possible results from the public dataset highlights the potential errors and consequences of single material data selection.

1. Introduction

The building industry contributes to 38% of the total global CO2 emissions[1]. There are two types of carbon emissions generated from a building: the embodied carbon and the operational carbon. The embodied carbon is the greenhouse gas (GHG) emission associated with the construction materials, including the raw resource extraction, materials processing, component assembly, transportation, construction, maintenance, deconstruction, and disposal. The operational carbon includes the GHG

emissions due to operation of the building[2]. The progress of operational carbon reduction has manifested through the advancement of building energy codes and ongoing research, and in the past few decades has been reflected in the change in building design and operational practices[3]**.** Although there is an increase in awareness and literature publication on embodied carbon in recent years, embodied carbon remains less studied in comparison to operational carbon.

The embodied carbon calculation is a part of the Life Cycle Assessment (LCA) of a building. LCA assesses a building's total carbon emission throughout its life cycle, including operational carbon and embodied carbon[4]. The demand for LCA in the building industry has been increasing due to efforts to mitigate the effects of climate change. As this methodology continues to mature, guidelines have become more developed, yet there are still significant discrepancies among reported LCA results in practice. This analysis process relies fundamentally on accessible data; however, data availability and accuracy remain an issue. The current building LCA studies rely heavily on commercial databases. The comparative database studies are mostly carried out by comparing building LCA analysis results performed by using a singular data selection method. This method involves using a single data point for each material from each database to perform LCA on the same structure, which can be potentially biased and produce limited results. Therefore, this study proposes a comparative framework for embodied carbon emissions databases to identify the underlying issues and difficulties, provide a fair method for data comparison within the databases, and assist the understanding of these databases' data availability and data homogeneity. The framework is applied to comparing three publicly available databases, EC3[5], the ICE Database[6], and the ÖKOBAUDAT Database[7]. An additional comparative life cycle embodied carbon assessment (LCECA) study on a multifamily house is carried out to evaluate the differences between the aggregate data from the three public databases and the commercial database Gabi Database in the LCA tool Tally[8].

2. Background

2.1 Types of LCA

In general, there are three LCA methods: the process-based method, the economic input-output method, and the hybrid method[9–11]. Process-based LCA is a bottom-up approach in which energy-use flows and patterns from the manufacturing and production level are used to calculate environmental impact[11]. The methods account for the process, manufacture and transportation, construction, maintenance, and post-processing emissions for all products used in the building, as well as the operational emissions from building usage[12]. The process-based method is capable of generating highly specific results in addition to precise breakdowns at different phases of the life cycle assessment. However, this method is primarily limited by data availability, truncation errors, and other various reasons affecting calculation accuracy and reliability[11,12]. Even so, process-based LCA is one of the most used LCA approaches, and the ISO environmental management standards are also based on this method[13,14]. Most LCA software on the market utilize process-based LCA specified in ISO 14040/14044[15].

The Economic Input-output LCA (IO-LCA) method estimates environmental emissions based on overall economic activities. IO-LCA is a mathematical procedure that uses industry transaction information and the direct environmental emissions of industries to estimate total supply chain emissions[9]. The main advantage of IO-LCA is that macroeconomic data upon which the calculation relies is widely available and provides a more comprehensive environmental assessment[16]. Unfortunately, the usage of macroeconomic data to perform LCA requires a large number of assumptions and lacks detail and specificity[17], limiting results to the economic sector, rather than the product of specific processes[16].

The hybrid LCA method is the combination of process-based LCA and IO-LCA. This type of method was developed with the intention of mitigating the truncation errors in process-based LCA and aggregation limitations in the IO-LCA method[18]. This method allows flexibility in incorporating the two methods according to the data ability, accuracy, and modelling conditions; however, the hybrid selection

can also inherit the disadvantages from both models[11]. There are several methods of hybrid LCA which vary the degree and method of integration between the two methods, such as the tiered hybrid analysis, IO-based analysis and integrated analysis[18].

Out of the three LCA methods listed above, the majority of studies in the construction field adopt the process-based LCA method due to its detail-oriented and product-specific characteristics[19]. Pan and Teng also agreed with Fenner et al. as they stated that the LCA tools building industry mainly adopts the process-based LCA[15].

2.2 Embodied Carbon Tool and Database-Related Comparative Assessment in the Building Industry

LCA comparison difficulties have been found in many studies. Moncaster and Song reviewed LCA results published in academic papers and highlighted the wide range of embodied energy and carbon values due to diverse product data derived from different LCA methodologies[20]. Fenner et al.'s study suggested the methodological differences for analyzing carbon emissions from a building made results difficult to compare[19]. Nwodo and Anumba's literature review identified the key challenges in building LCA, including comparison difficulty, transparency, data quality, and uncertainty[21]. There are significant challenges in directly comparing the databases since the data sources and calculation methods vary[22]. There have been several studies aimed at comparing or accessing databases used for performing building LCA in the past. Of those, many indicated a discrepancy in the LCA results from the target databases[22–27]. Takano et al. suggest the result of the comparison concluded that the databases demonstrated similar trends and produced results of the same order of magnitude but still lacked agreement[22]. Lasvaxs et al. concluded that the EPD databases could show different values depending on the environmental indicator, and global warming potential showed approximately 25% deviation[23]. Sinha et al.'s study showed that the energy footprint result was similar for all three tools, but the total GHG emission intensity varied due to location differences[24]. Speck et al. assessed LCA software by making a conscious effort to keep the input

data identical, and the results are still different due to the methodology used in the LCA software[25]. Teng et al.'s comparison results showed inconsistency between the databases mainly due to the limited quantity of construction material data available, inconsistent LCA system boundaries among the databases, and geographical differences in the material extraction and electricity generation[28]. Emami et al. compared databases by selecting the best-fit materials from the LCA tools to perform LCA on two buildings. Their results showed very different results on a whole building level[26]. Pauer et al. suggested that the discrepancy between the results for climate change is a 9% difference between the databases of study[29]. Mohebbi et al. compared a more general type of database with a more detailed database. The result from the more detailed database could have 35.2% embodied carbon reduction compared to the result obtained from the general database[27].

Many of the studies mentioned above follow the format of conducting a basic tool/database comparison and followed with case studies of a whole or partial building LCA analysis to compare the results from the different tools and databases. The majority of the studies agreed on the discrepancy of results obtained by using different databases. Out of the studies that included case studies, apart from one case, the selection of input data is often not mentioned, or the best fit data from each database/tool is chosen to evaluate LCA results on the same building/structure. The lack of an input selection method or the subjective comparison based on a single data point from each database can hinder the accuracy of the results obtained from the case studies.

2.3 LCA data quality and availability

Data quality and availability are the major issues causing the lack of LCA comparison. There have been studies focusing on data quality and availability database comparison. Hu and Esram pointed out that in general, the databases require improvements in standardization, transparency, regular maintenance, and documentation. Some databases lack data sources and collection process information

or are only provided in reference reports, making them difficult to discover. In addition to the databases, the tools require transparency and quality assurance. They also highlighted the lack of standard testing procedures to compare or evaluate the results from the tools[3]. Pan and Teng investigated different variables and their numeric influence on embodied carbon. Their literature review included the inspection of the existing LCA software and databases and found that some countries provide open-access national databases of construction materials, which are not versatile due to regional limitations. Pan and Teng also established a framework to examine four methodological dimensions to describe these differences: temporal differences, spatial disparities, procedural inconsistencies, and physical diversities[15]. In Richardson's doctoral thesis, he listed the factors of the data source for embodied carbon calculation in the building industry and ranked them according to data quality: 1. EPD (EN 15804 compliant) 2. Factor from commercial LCA database 3. PAS 2050 compliant carbon footprint 4. Industry data 5. Government data 6. Factor derived/aggregated from literature. From his expert survey evaluation, he concluded that in general, EPD data should be used when available[30].

In addition, LCA uncertainties are often overlooked in building LCA, as the majority of studies do not include uncertainties. There are several approaches to LCA uncertainties; Heijung and Huijbregts identified four types of approaches: scientific, constructivist, legal, and statistical[31]. Richard reviewed the Dutch National Institute for Public Health and the Environment and created a guide for uncertainty assessment, indicating the types of uncertainty to be used on different occasions. The quantitative methods identified in the guide are sensitivity analysis, error propagation, and Monte-Carlo analysis[30,32].

2.4 Standards

ISO has released primary standards for conducting LCAs: ISO 14040 environmental management life-cycle assessment principles and framework and ISO 14044 environmental management life-cycle assessment requirements and guidelines.[14,33] These two standards provide general LCA guidelines but do

not indicate detailed evaluation methods or techniques. This gap has led to the development of a variety of LCA methods and tools.[3] In addition to the ISO standards, there are a set of European standards that address LCA in the built environment. EN 15978 is a standard for building level LCA and sets out organized principles, including the four stages of the life cycle and their subcategories: product (stage A1-3), construction (stage A4-5), use (stage B1-7), and end of life (stage C1-4).[34] It is important to point out that the ISO standards require LCA to include information on uncertainties addressed in sections 4.3 i), 5.4.3 in ISO 14040, and throughout the standard in ISO 14044, but it is not mandatory in EN 15978. [14,30,33,34] There are several standards relevant to construction products. ISO 14025:2011 and ISO 21930:2017 are regulations set at a general level.[35,36] EN 15804:2012+A2:2019 regulates the EPDs for construction materials.[37] However, EN 15804 only requires cradle to gate stages (A1-A3) to be included in the EPDs.[38]

3. Framework

3.1 Framework Development

The framework for embodied carbon database comparison is developed following a four-step procedure. The first step examines the existing literature comparing embodied carbon databases and summarizes the metrics implemented in these reviews. The second step identifies the information necessary to perform a life cycle embodied carbon assessment (LCECA) calculation. The third step takes the findings from the previous steps to identify gaps between existing methods by comparing embodied carbon databases and requirements for LCECA from the calculation perspective. The last step builds on the third step and determines the necessary procedures and parameters to evaluate the databases in a commensurable manner.

Step 1: Existing database comparison literature

From the literature review, there are six cases involved with direct database comparison. The fields of examination from the literature cases are aggregated, summarized, and categorized in Table 1.

These studies have mainly assessed the database on its general background information without examination and analysis of the data within the databases.

General Database Comparison Parameters				
Basic Information	Data Quality	Data Quantity	Data Diversity	Accessibility
• Last Update • Organization • Origin	• Data Source (Industry, gov, com etc.)	• Number of Data	• Region • Material Categories • LCA stages	• Cost • Licence

Notes:
1. Chart listed common fields on 6 papers with general database comparison in a chart form

Table 1: Common General Database Comparison Parameters

Step 2: Life Cycle Embodied Carbon Calculation Requirements

In order to assess the total embodied carbon of a building, the calculation must be performed. The life cycle embodied carbon of a building can be calculated with the following equations:

$$EC_b = \sum_m EC_m \tag{1}$$

$$EC_m = Q_m \times \sum_{LS} ECF_{LS} \tag{2}$$

In Equation (1), The life cycle embodied carbon of a building (EC_b) is calculated as the sum of the life cycle embodied carbon contributions from materials used in the building (EC_m). The life cycle embodied carbon of individual materials can be calculated using Equation (2) by multiplying the quantity of the material (Q_m) with the sum of the embodied carbon factor of the material at each life cycle stage identified in the standard EN15978 (ECF_{LS}) (Figure 1).

The information required from the database are embodied carbon factors that correspond with materials found in a building's bill of materials. The embodied carbon factors in these databases are commonly expressed as Global Warming Potential per unit of material (kgCO2e/unit of material).

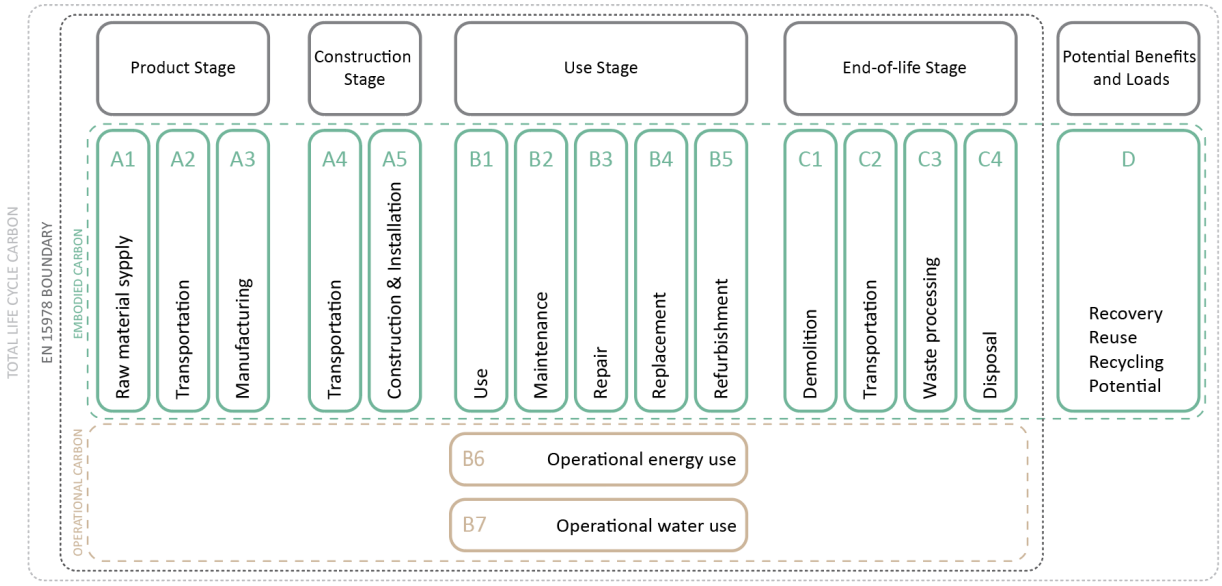


Figure 1: LCA Stages

Step 3: Identify the Gap

From examining the current database comparison methods and the requirements for LCECA calculations, there is a gap in existing comparative methods from the perspective of calculation feasibility. The current methods focus on looking at a database's quality as a whole, which is a very important initial step to understanding the database's overall scope and usefulness. However, to perform a life cycle embodied carbon calculation, numerical values from the databases are directly engaged. Therefore, it is necessary to create a framework for quantitatively assessing the data within a database to aid the purpose of LCECA calculations.

Step 4: Framework Development

The last step builds on the third step and determines framework parameters to evaluate the databases in a commensurable manner. In order to compare data in a commensurable way, the functional unit for embodied carbon factors must be consistent throughout the entire comparison as well. The evaluation parameters are based on the two pieces of information necessary for the calculation, with the

goals of understanding the embodied carbon factors of materials in the same category as well as understanding these factors from a life cycle stage aspect.

3.2 Framework

Step 1: Gather background information and data from target databases

Step 2: Convert data to have a uniform functional unit for embodied carbon factors

Step 3: Group the data by categories and LCA Stages (reassigning categories may be required)

Step 4: Compare databases through a series of data visualization from material category and LCA stage perspectives

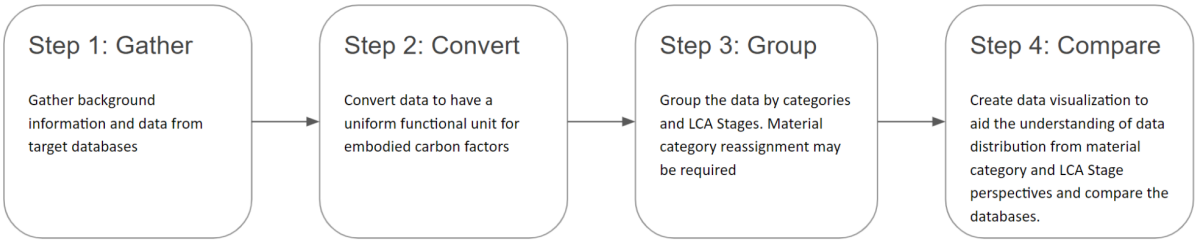


Figure 2: Embodied Carbon Database Comparison Framework

3.3 Framework Case Study

Difficulty with Existing Databases

In order to compare data within databases, access to the database is the key challenge. The databases used in the thirteen works of literature with both direct and indirect database comparisons are examined. The top 10 LCA databases used in these studies are summarized in Table 2. 77% of the study used one or more commercial databases that would require a significant investment to access. The cost

of database access can be a hindrance to LCEC analysis as it is unaffordable for many smaller-scale firms and the general public.

Database	Count	Cost
Ecoinvent	9	€ 3'800 - € 4'400
GaBi Database	7	~ 3,000 USD
U.S.LCI	4	Free
ETH-ESU 96	3	Free
INIES	3	Free
ICE	2	Free
Base Carbone	2	Free
Environmental Footprint	2	€2,250 -€4,750
Athena	2	Free

Table 2: Common Databases From Literature

In addition to the cost barrier, the technicality of databases poses further challenges to data comparison. The LCA databases for construction materials come in many different formats. The common ones include the downloadable International Life Cycle Data system formats (ILCD) in Extensible Markup Language (.xml), Comma Separated Values (.csv), Spreadsheet (.xlsx) and JavaScript Object Notation (.json). Most of these whole packages are difficult to compare and extract information without extensive data parsing and data analysis. The difficulty of parsing each format is shown in Figure 3.

Some databases compile all the data into one downloadable package, while others host data on a web table, where each data point has to be downloaded individually. Some examples include databases hosted on sites such as ECO PORTAL and IBU Data. These databases' web pages often offer rudimentary data filter systems, including fields such as material name, location, and data validity, as well as links to more detailed information on individual data and some downloadable format such as .xml, .csv, or .pdf

format. However, these formats do not include any visual comparisons of detailed information about the data.

In the unique case of the EC3 building transparency database, the entire database is hosted through an application programming interface (API) and has a well-developed front end. The website allows the user to select data by category and has detailed filters tailored specifically for each material category. The front end also provides detailed GWP values of individual materials as well as statistical values of the material category displayed in a box plot. While practical for selecting materials, these functions are still difficult for analysis of the data both within and across different databases.

Given successful access to a database, the next challenge is comparing the embodied carbon factors of the data. The examination of five databases, Base Carbone, EC3, EPD Italy, ICE, and ÖKOBAUDAT (OBD), demonstrated many different reported functional units of the materials (Appendix A). The inconsistency of functional units makes a fair comparison between data and databases difficult. Of these databases, EC3, ICE and OBD include conversion factors or common units of material or measurement, making embodied carbon comparison possible with the same functional unit of kgCO2e/kg of material. Therefore, these three databases are chosen for analysis and case study.

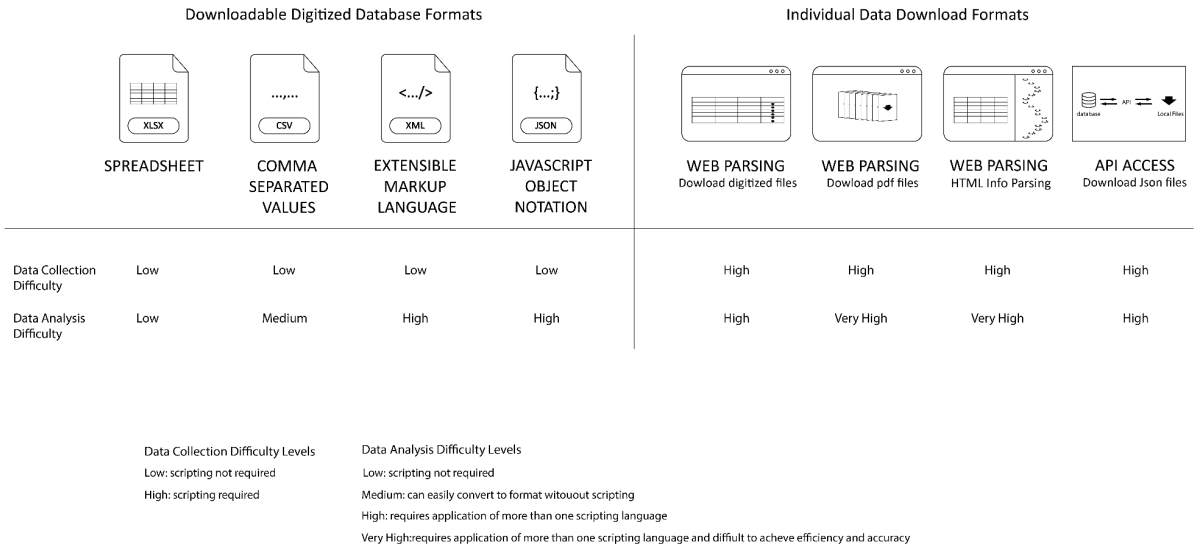


Figure 3: Illustration of data accessibility difficulty

Step 1:Gather background information and data from target databases

Each of the target databases has its general comparison parameters and information listed in Table 3. The chart shows the basic similarities and differences between the three databases. In recent years, all three databases have been updated, but ICE is updated less frequently than the others. The three databases have different origins, and their data are mainly focused on the originated location. The source of data is different in all three cases. EC3's sources are from Third Party Verified EPDs; ICE's data is based on literature; and the German government provides OBD's data. The quantity of the data from each database varies significantly as well; EC3 has more than 80,000 data points while ICE only has about 500. From initial observation, all three databases focus on only construction materials. In terms of LCA stages, both ICE and EC3 databases concentrate on stages A1 to A3, whereas OBD contains information on all stages. The accessibility section demonstrates that the databases are all free and open to the public.

EC3 - General Database Comparison Parameters									
Basic Information		Data Quality		Data Quantity		Data Diversity		Accessibility	
Last Update	2022	Data Source	Third Pary Varified EPDs	Number of Data	>80,000	Region	mainly USA, some Global	Cost	Free
Organization	Building Transparency					Material Categories	Construction	Licence	N/A
Origin	USA					LCA stages	A1-A3		

ICE - General Database Comparison Parameters									
Basic Information		Data Quality		Data Quantity		Data Diversity		Accessibility	
Last Update	2019	Data Source	Emission factors from	Number of Data	>500	Region	mainly UK	Cost	Free
Organization	University of Bath		Universities & Research Institutions			Material Categories	Construction	Licence	N/A
Origin	UK					LCA stages	mainly A1-A3, some D		

OBD - General Database Comparison Parameters									
Basic Information		Data Quality		Data Quantity		Data Diversity		Accessibility	
Last Update	2022	Data Source	Emission factors from	Number of Data	>1,400	Region	mainly DE	Cost	Free
Organization	German Federal Ministry for Housing		Government source			Material Categories	Construction	Licence	N/A
Origin	DE					LCA Stages	All		

Table 3: General Database Comparison Information

Data Gathering:

- ICE: Data downloaded directly from the website in Spreadsheet format (.xlsx), then converted to Comma Separated Values (.csv) format.

- EC3: Data accessed from API and downloaded in individual JavaScript Object Notation (.json) format files.
- OBD: Data downloaded directly from the website in Comma Separated Values (.csv) format. This database is also available in .xml format.

Step 2: Convert data to have a uniform functional unit for embodied carbon factors

In order to compare the data, they must all be converted to the same units. The original data are in many different units such as volume, surface area, length, mass, etc. (Figure 4). Often the mass of the material in kg is used for comparison. Databases like EC3 and ICE included the converted Embodied Carbon Factor values - which is measured in kgCO2e/kg of material. Initially, this study included ten databases; however, 7 out of 10 failed to have properly recorded units or units of conversion factors, so they are excluded from the case study. The EFC values of the OBD database are in kgCO2e per declared unit, which means conversion must be carried out, and luckily, OBD did include conversion factors for most of their data. Even then, 26% of the data from OBD was missing conversion factors usable for the next comparison stage. Figure 5 shows data eliminated due to the lack of conversion units. By examining these fields, it seems like mechanical equipment takes up one of the largest categories, usually declared in an individual piece of equipment. For mechanical equipment, it makes sense to study these materials categories separately.

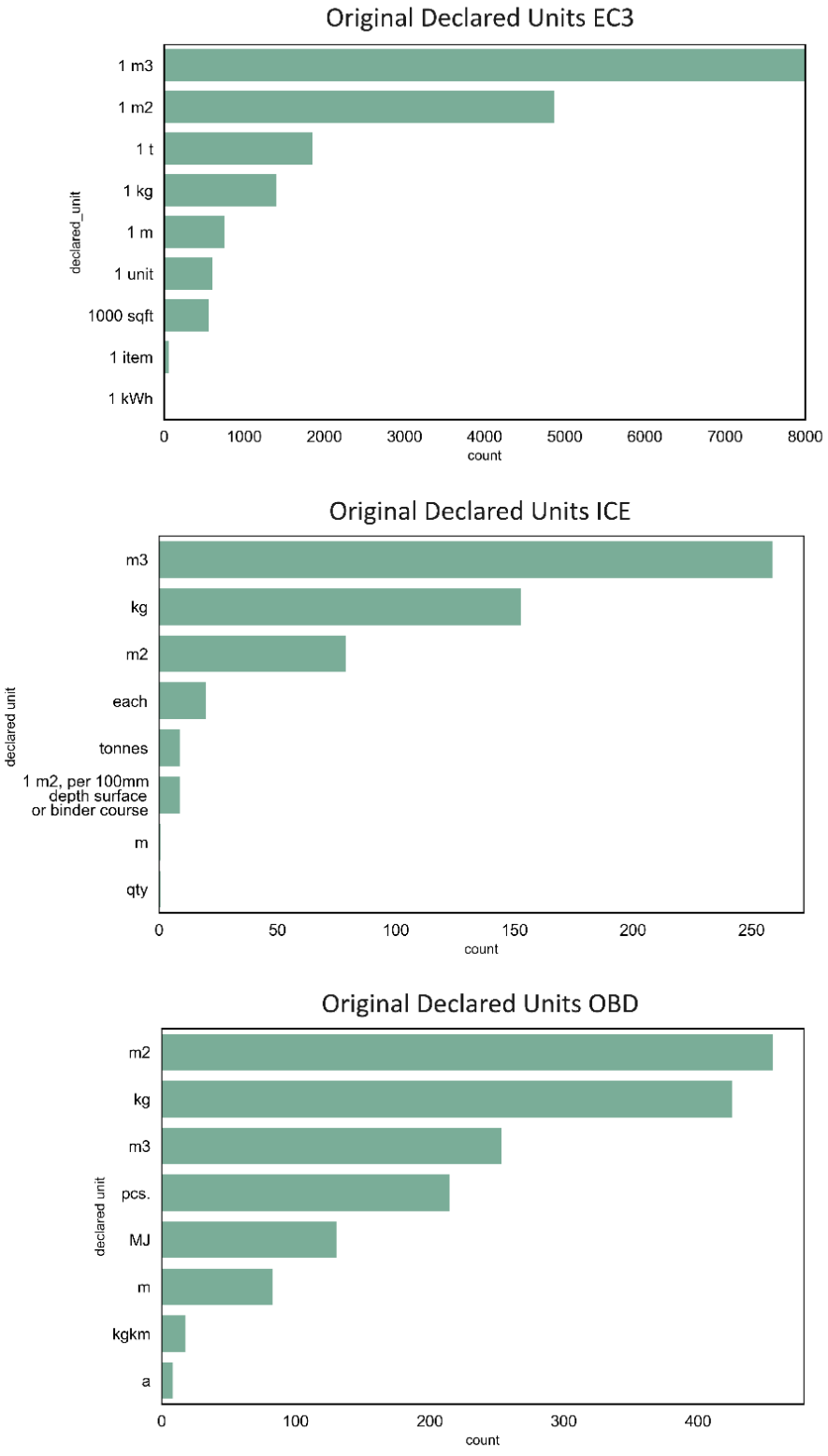


Figure 4: Types of Units from EC3, ICE, and OBD

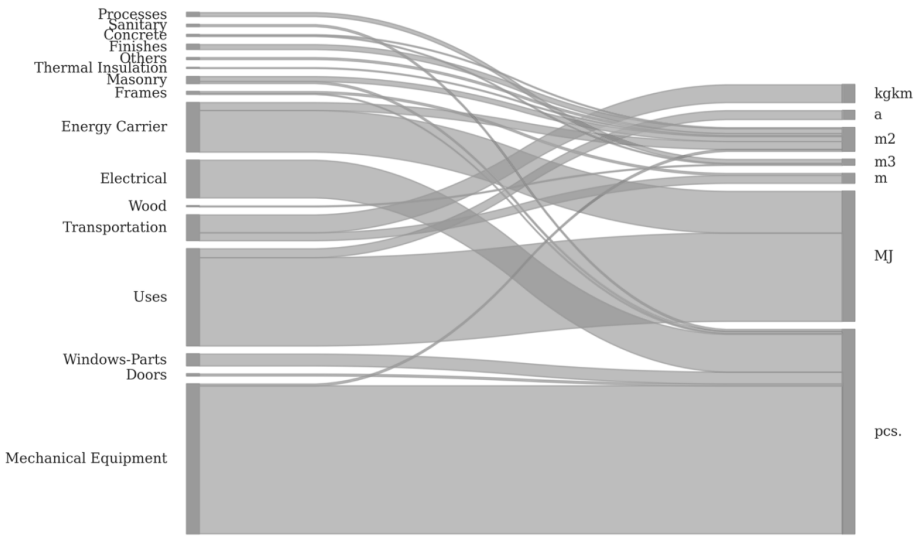


Figure 5: Data Eliminated from OBD

Step 3: Group the data by categories and LCA Stages.

The initial categorical study in Figure 6 demonstrates that each database's type of building materials and categorization method vary. It is still challenging to find all the matching categories by only examining the general categories. Thus, material recategorization is performed in order to compare the data with the same material category. The detailed categories from each database are listed in Appendix B, and the common categories are isolated and categorized for comparison as shown in Appendix C. It is evident from the lists that both EC3 and OBD have significantly more material variety than ICE. The material categories common to all three categories include aluminum, asphalt, cement, concrete, glass/glazing, steel, and wood. The materials in these categories are further compared individually in the next step. The LCA stages are standardized for all databases, therefore regrouping is unnecessary.

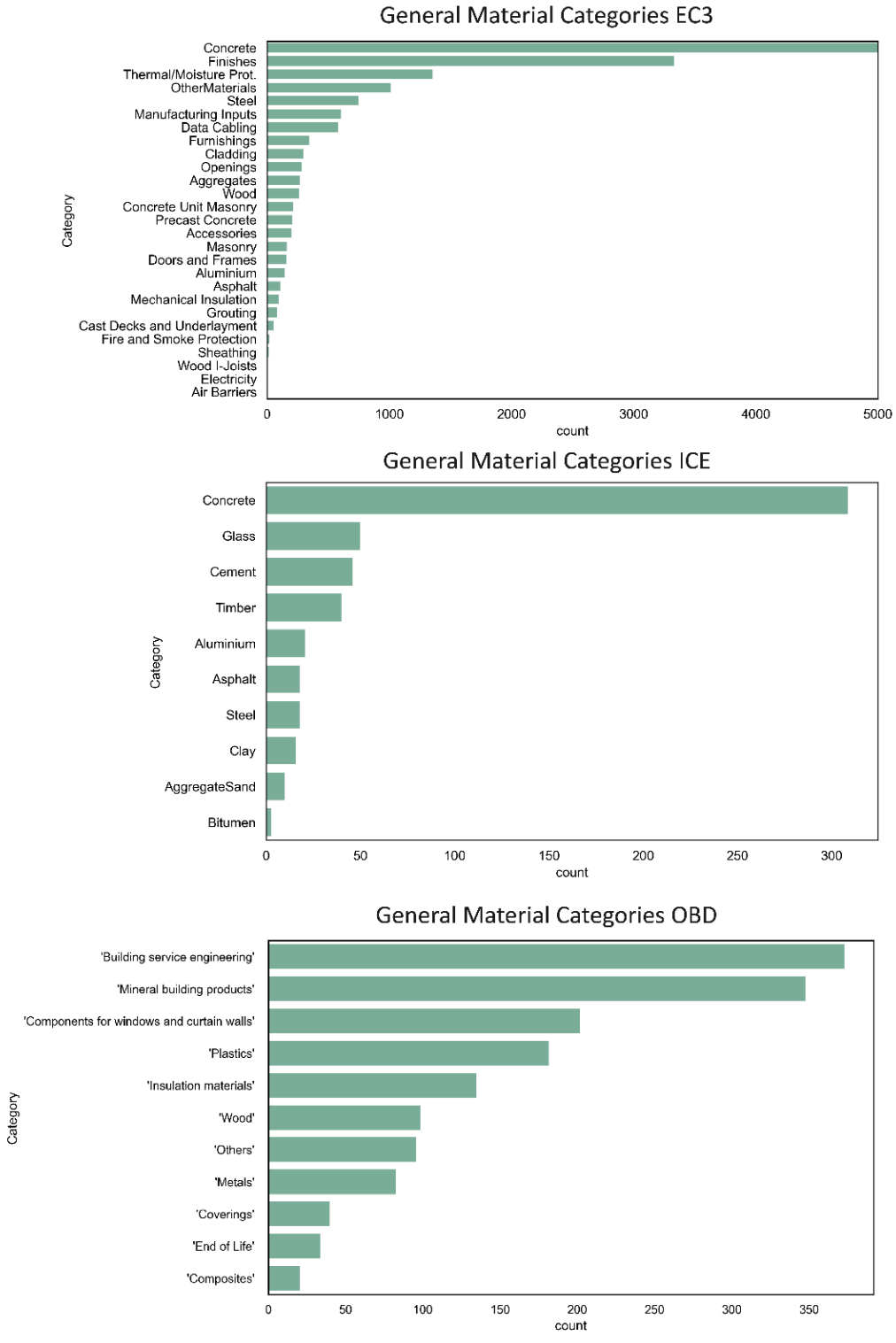


Figure 6: General Material Categories from EC3, ICE, and OBD

Step 4: Compare databases through a series of data visualizations from material category and LCA stage perspectives

To compare the databases from both the material category and LCA perspectives, two sets of analyses, data quantity analysis and GWP distribution analysis, are performed. In the first set of analyses, the data quantity of each database is analyzed by examining the LCA stage versus region (Figure 7) and LCA stages versus common material categories plots (Figure 8).

The LCA stage versus region data quantity analysis is demonstrated by the two sets of charts in Figure 7. The chart on the left shows the data density by the magnitude of the quantity of data, and the chart on the right shows the distribution of the percentage of data within each database. This chart adds a quantitative perspective to the LCA stages and regional coverage in the general comparison charts collected in Step 1. This chart highlights that the data from the Americas make up most of the EC3 database by percentage along with a significant amount of data from the Europe and Oceania Regions. Compared to EC3, ICE and OBD have significantly less data, and the ICE database concentrates on the European region with sparse data from the other regions. In contrast, OBD only has data from the European Region. From the LCA stage perspective, the chart also suggests that not all data contains all the LCA stages listed in the general description. In the case of ICE, the percentage of data containing D stage information is significantly less than stages A1-A3. The majority of the data in the ICE database contains GWP information on stages A1-A3 information while only 7% of the data have GWP information on stage D. In the case of OBD, the majority of the data contains A1-A3 information. In OBD, overall, more than 40% of the data have GWP information on stages C1 - C4 and stage D. Despite the optimistic coverage of the stages A1-A3, C and D, less than 40% of the data have information on stages A4 and A5 and less than 20% of the data have information on any of the B stages.

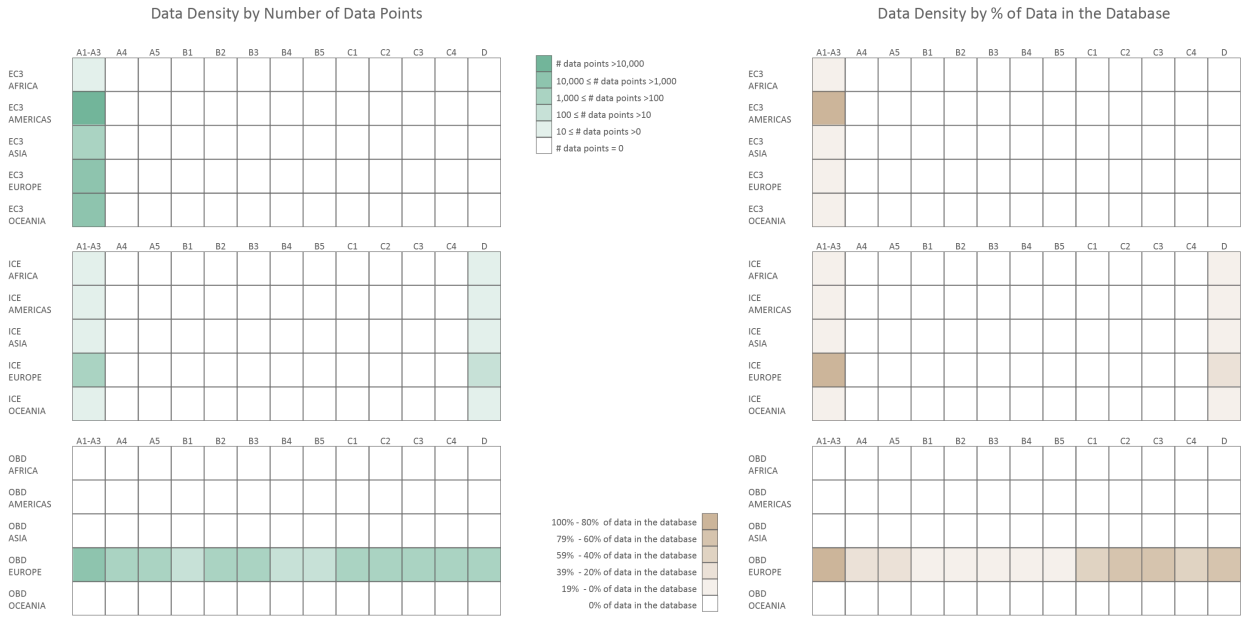


Figure 7: Quantity of data in databases by LCA Stages

Similar to the LCA stage versus region data quantity analysis, the LCA stage versus common material category analysis is shown in the two sets of charts by magnitude and percentage (Figure 8). This chart is based on the seven common categories of the three databases recategorized in Step 3. There are a few outstanding observations from this chart. First, even though EC3 has a large database size, the concrete category constitutes more than 95% of the data in the database. The ICE database shares the characteristic of a concrete-concentrated database, with 58% of data under the concrete category. Different from EC3 and ICE, OBD has a more even distribution of data quantity in each material category, but concrete is the category with the most comprehensive LCA stage data. In OBD, with the listed common categories, only wood and concrete categories have information on all the embodied carbon LCA stages. Compared to the concrete category that has information on all the listed stages at the same magnitude, the B stages and C4 for the wood category have fewer data than the other stages of the wood category. In general, like the previous graphs, there is a significant lack of data in the B stages.

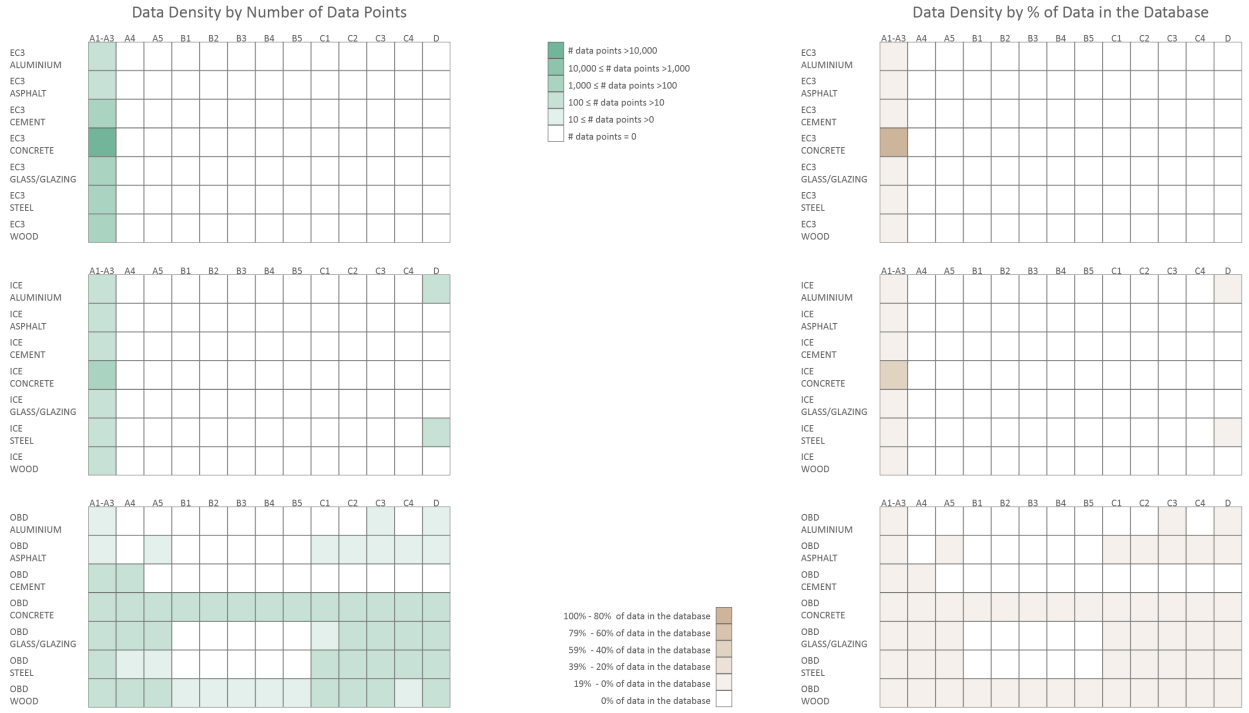


Figure 8: Quantity of data in databases by Common Material Category and LCA Stages

The second set of analyses further examines the distribution of material category GWP values. The LCA stage versus material category GWP values analysis is demonstrated by the two sets of graphs. The first set of graphs is the kernel density estimation plots visualizing the probability of GWP density for each of the common materials organized in LCA stages (Figure 9). The second set of graphs shows box plots that provide a more detailed comparison of the databases' GWP values of each material category for stages A1-A3 (Figure 10). Statistical values for the box plots are included in Appendix D. The findings of the analysis focus on stages A1-A3 since three databases have a significant quantity of data for comparison.

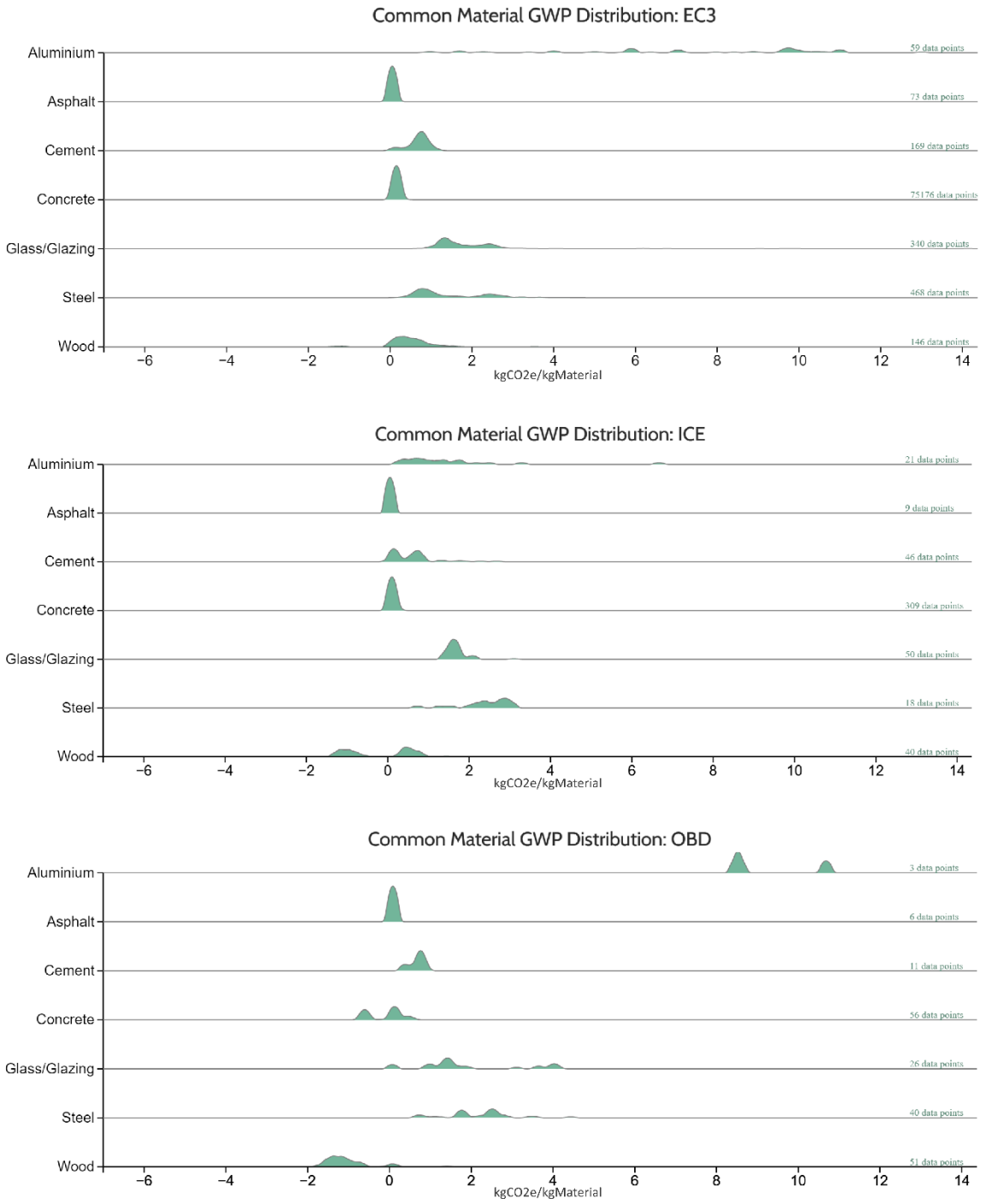


Figure 9: Common Material GWP Distribution

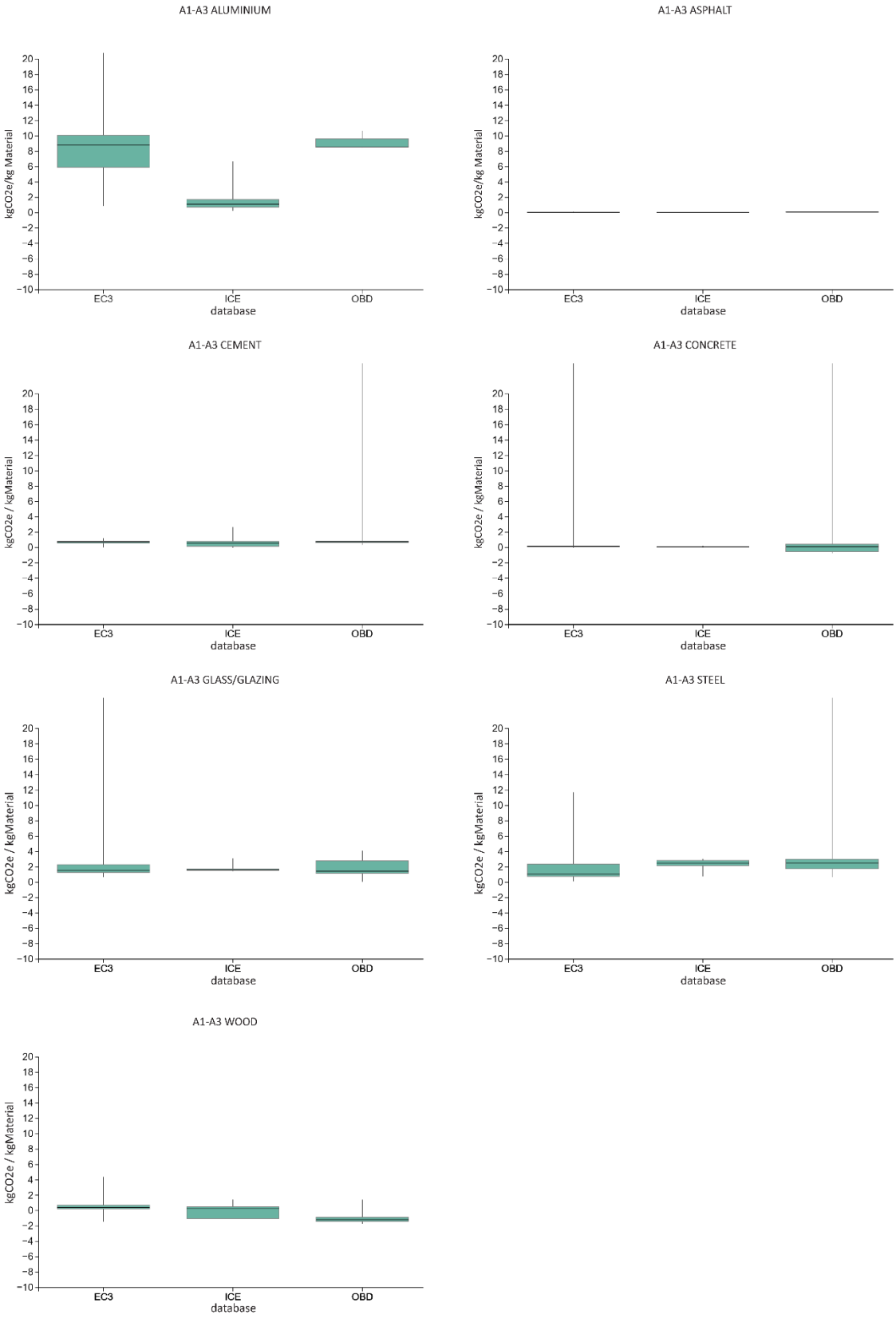


Figure 10: Common Material GWP Boxplots

Material homogeneity within the database

Within each database, some material categories exhibit more homogeneous GWP values than others. From observation, EC3's homogeneous material categories include asphalt and concrete. Similar to EC3, in ICE, asphalt and concrete are homogeneous. In OBD, only asphalt is the homogeneous material. In general, asphalt has a small range of GWP values, and aluminum, glass/glazing, and steel have a large range of GWP values in each of the databases.

Material homogeneity across three databases

After understanding the range of GWP values within each database, it is also essential to compare the values between the databases. By examining the mean of each material across the three databases, there are many cases where the outliers skewed the mean value significantly. Therefore, to reduce the skewness caused by the outliers, the median value is used for comparison. From observation, the material categories that appear to be more homogenous across the databases include asphalt, cement, concrete and glass/glazing.

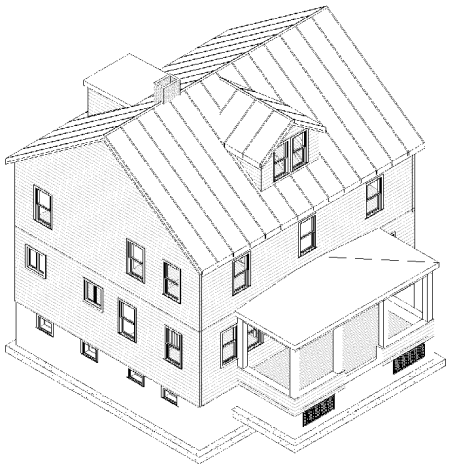
3.4 Framework Results

There are three main conclusions from the framework study. First, the framework identifies the underlying issues and difficulties in the comparison of embodied carbon databases from an accessibility perspective. Second, the framework provides a fair method for quantitative data comparison within the databases. Last, it assists the understanding of data availability and data homogeneity of these databases.

4. Comparative LCECA study4.1 Comparative LCECA study method

The second part of the study examines the application of the framework with LCECA studies by using the statistical values of material categories of the data collected from the three databases EC3, ICE

and OBD, combined as a dataset (EIOD) as well as identifying the similarities and differences between a typical LCECA study performed using a commercial tool and database versus the LCECA performed with publicly available databases. A single family house design is selected as the base of the LCECA analysis. The LCECA study is performed by using the Gabi Database in Tally based on the BIM model of the design in Revit (Figure 11). The system boundary of this study is limited to structure, envelope, foundation, and interiors, and LCA results from Tally include LCA stages A1-A3, B2 - B5, C2 - C4, and D. The material used in the building is recategorized in their general category for comparison. Based on the building material categories, the EIOD's embodied carbon factor values in kgCO2e/kg of material are computed for each category and each LCA stage, matching that of the stages from Gabi-Tally. It is important to note that categories including gypsum, insulation, membrane, and paint are only based on EC3 and OBD as they are not included in the ICE database. Moreover, as the comparative data showed in the previous part of the case study, stages other than A1-3 and D are based solely on OBD data. There are multiple materials missing information from these stages (Appendix E). These values are filled in as zero values for calculations. The values under stages A1-A3, C2-C4, and D are multiplied by the mass of the materials, while the values under stages B2-B5 are multiplied by the replacement mass of the materials. The sum of these values is the total LCECA GWP values for EIOD.



Materials	Mass in kg	Replacement Mass in kg
Aluminium	40.85	40.85
Asphalt	2075.89	4151.78
Brick	6208.74	0.00
Cement	17746.78	66.15
Concrete	120465.69	0.00
Glass/Glazing	1400.67	1400.67
Gypsum	314.34	314.34
Insulation	203.21	33.33
Membrane	82.58	0.00
Paint	143.55	1113.01
Steel	3655.94	65.27
Wood	25341.21	22937.16

Service Life: 60 years

Figure 11: Material Quantity and Model for the LCECA Study

4.2 LCA Results

The overall results of the LCECA studies, normalized to kgCO2e/sqm, are listed in Figure 12. The LCECA results generated from the commercial tool method do not include biogenic carbon. The public databases' LCECA results are presented in their statistical values. The difference between the public mean result, and the commercial result is 149%, and the difference between public median result and the commercial result is 53%. The commercial result falls just below the first quartile of the public result. By looking at the minimum and maximum range of possible results from the public dataset, it is important to highlight the potential error and consequence of individual data selection.

LCA	kgCO2e/sqm
EIO Mean	1994.69
EIO Median	500.56
EIO Min	-16936.24
EIO Max	171149.44
EIO Q1	297.44
EIO Q3	5068.76
Gabi-Tally Exclude Biogenic Carbon	290.98

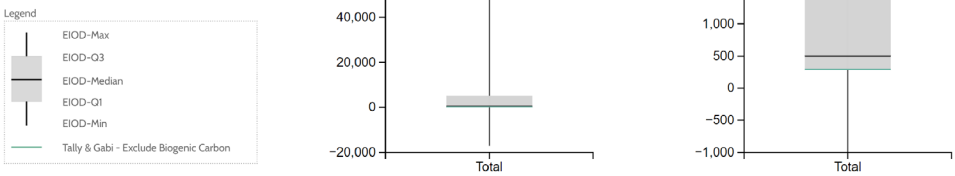


Figure 12 - Overall LCECA Results

Looking closely at the results, the normalized values are graphed by each LCA stage (Figure 13). This graph highlights that in stages A1 to A3, the public Median and commercial results are relatively close, with a difference of 18%. The range for A4 is significantly smaller than the other LCA stages. Results of stages B, C and D are inconclusive due to the sparse data from the public database set.

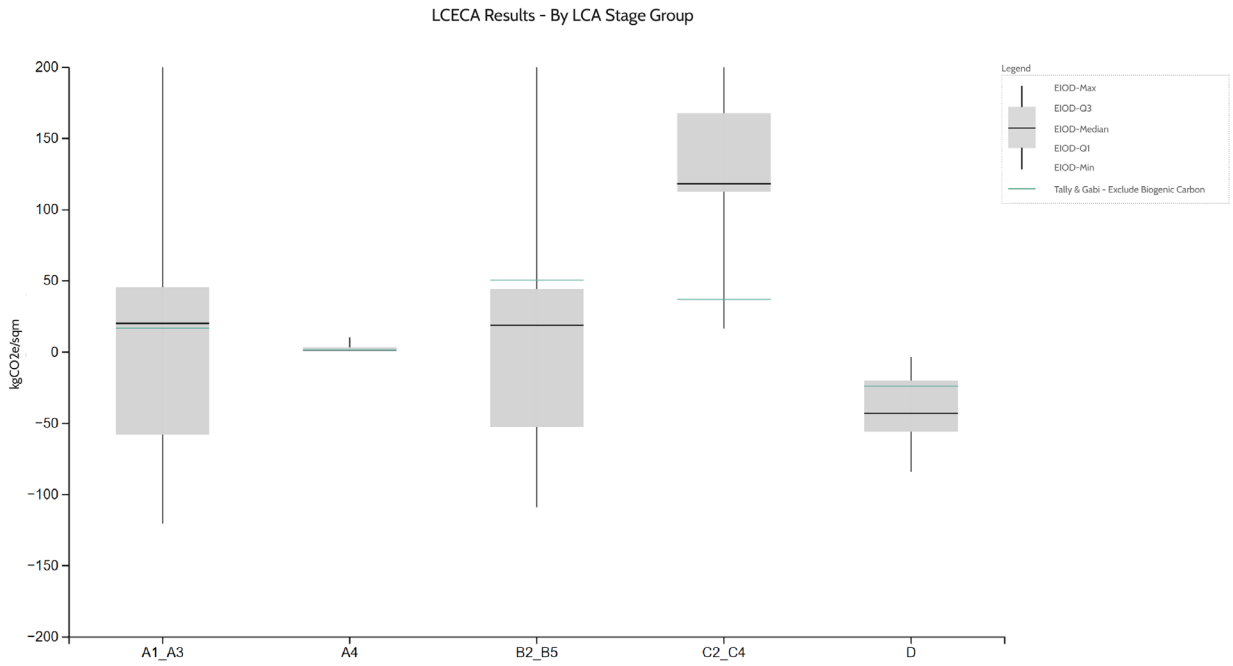


Figure 13: LCECA Results by LCA Stage Group

To examine the results from a material aspect, the normalized results are graphed for the A1-A3 stage (Figure 14). The graph suggests that the general trends are similar for the commercial and public median results, except for insulation. This graph further demonstrated the widespread EC range for materials such as brick, cement, concrete, glass, steel, and wood. For materials that have a more homogenous embodied carbon factor or a smaller overall quantity, individual data selection will still produce reasonable results; however, for materials with greater quantity and larger embodied carbon factor spread, it is better to use a holistic value such as the median value for calculation.

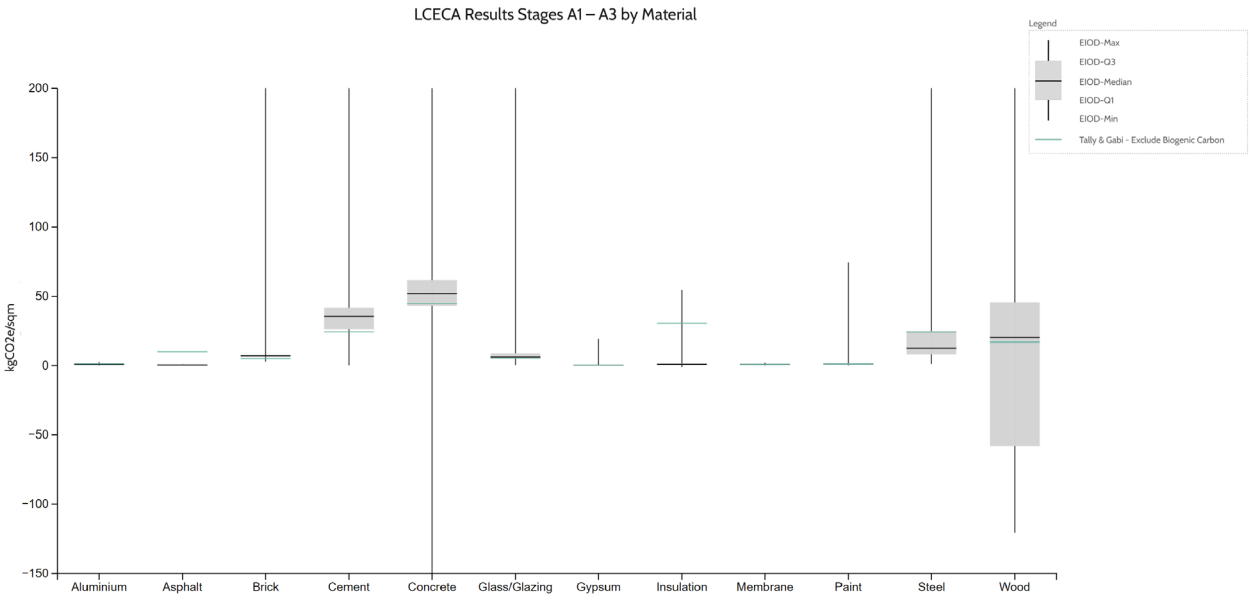


Figure 14: LCECA Results Stages A1 – A3 by Material

This comparative LCECA study suggests that the median embodied carbon factors values of the materials from the aggregated public database provide a reasonable LCECA compared to the commercial data. In addition, the result of embodied carbon factors value ranges should still be included in the commercial database to show the potential error ranges.

Limitations

This study is still at an early stage, and there are limitations. First, the study only includes the three databases, with only one building used for the LCECA study. The databases chosen are limited to processed-based LCA data on products, and the database framework has a limited focus on other data evaluation parameters, such as regional differences, which should be addressed in future studies. Moreover, a comparative analysis of commercial databases with the same framework should be included for a comprehensive comparison between the private and public databases.

Conclusion

This thesis includes the development of a four-step framework that aids the comparison of building embodied carbon emissions databases. The framework's applicability is demonstrated by comparing three databases: EC3, ICE, and OBD. The framework offers a fair method for quantitative data comparison within the databases and assists the understanding of data availability and data homogeneity of these databases. The comparison results highlight the missing LCA stage information in each database, the domination of concrete materials in data quantity, the material category's embodied carbon factor homogeneity of common materials in stages A1-A3 (asphalt) and the material category's embodied carbon factor homogeneity in stages A1-A3 between the databases (asphalt, cement, concrete and glass/glazing). The comparison suggests the underlying issues and difficulties in the comparison of embodied carbon databases, such as data access difficulties and a lack of unit documentation or conversion factors.

The LCECA study of a single-family house performed by using the aggregated data from the three public databases and the commercial database Gabi Database in Tally shows that the median embodied carbon factors of the materials from the aggregated public database provide a reasonable LCA compared to the commercial data. The study also notes that the commercial database should show the potential error ranges of the result for a more informative and accurate representation of the embodied carbon emissions.

This thesis also suggests recommendations for the future. The embodied carbon factor data should require a consistent digitized format, and embodied carbon factor data should continue to include more LCA stages, as only A1-A3 is required at this point. Also, databases should urge data providers to include conversion factors to mass to aid fair data comparison. For regulation and benchmarking for certification and subsidy programs, the government should take on the lead in managing and maintaining

a national database to ensure the coverage of a variety of material categories and LCA stages and other relevant parameters.

References

1. United Nations Environment Programme & Global Alliance for Buildings and Construction. 2020 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector - Executive Summary. (2020).
2. Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L. & Acquaye, A. Operational vs. embodied emissions in buildings—A review of current trends. *Energy Build.* **66**, 232–245 (2013).
3. Hu, M. & Esram, N. W. The Status of Embodied Carbon in Building Practice and Research in the United States: A Systematic Investigation. *Sustainability* **13**, 12961 (2021).
4. Müller, L. J. *et al.* A Guideline for Life Cycle Assessment of Carbon Capture and Utilization. *Front. Energy Res.* **8**, 15 (2020).
5. EC3 Resources. *Building Transparency* https://www.buildingtransparency.org/ec3-resources/ (2019).
6. Embodied Carbon Footprint Database. *Circular Ecology* https://circularecology.com/embodied-carbon-footprint-database.html.
7. ÖKOBAUDAT. https://www.oekobaudat.de/en/service/downloads.html.
8. Tally. https://www.choosetally.com/.
9. CMU, S. M. CMU - Economic Input-Output Life Cycle Assessment - Carnegie Mellon University. http://www.eiolca.net/ (2008).
10. Finnveden, G. *et al.* Recent developments in Life Cycle Assessment. *J. Environ. Manage.* **91**, 1–21 (2009).
11. Kwok, K. Y. G., Kim, J., Chong, W. K. O. & Ariaratnam, S. T. Structuring a Comprehensive Carbon-Emission Framework for the Whole Lifecycle of Building, Operation, and Construction. *J. Archit. Eng.* **22**, 04016006 (2016).

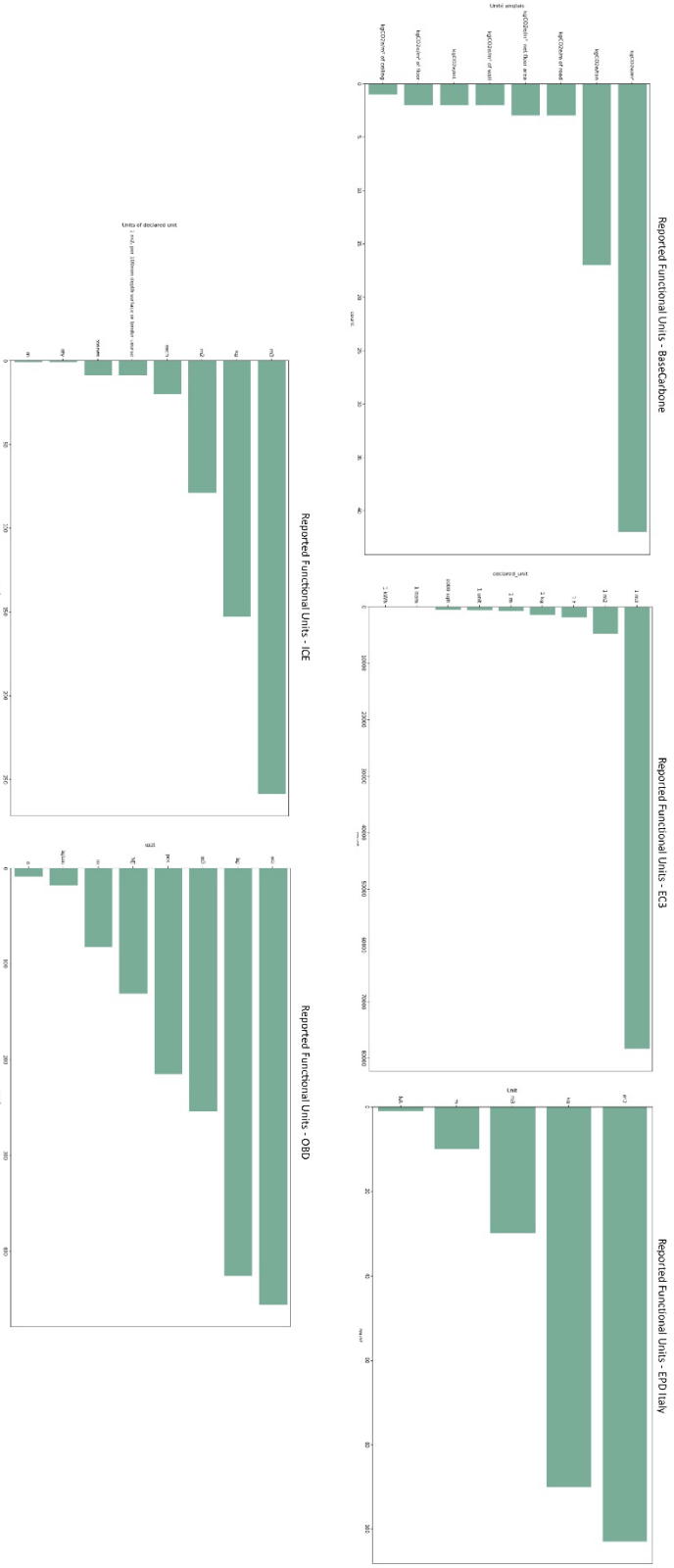
12. *Embodied Carbon in Buildings: Measurement, Management, and Mitigation*. (Springer International Publishing, 2018). doi:10.1007/978-3-319-72796-7.
13. Zeng, R. & Chini, A. A review of research on embodied energy of buildings using bibliometric analysis. *Energy Build.* **155**, 172–184 (2017).
14. ISO 14040 Environmental management - life cycle assessment - principles and framework. (2006).
15. Pan, W. A Systematic Investigation into the Methodological Variables of Embodied Carbon Assessment of Buildings. *Renew. Sustain. Energy Rev.* 14 (2021).
16. Azari, R. Life Cycle Energy Consumption of Buildings; Embodied + Operational. in *Sustainable Construction Technologies* 123–144 (Elsevier, 2019). doi:10.1016/B978-0-12-811749-1.00004-3.
17. Chong, W. K. & Hermreck, C. Understanding transportation energy and technical metabolism of construction waste recycling. *Resour. Conserv. Recycl.* **54**, 579–590 (2010).
18. Suh, S. & Huppes, G. Methods for Life Cycle Inventory of a product. *J. Clean. Prod.* **13**, 687–697 (2005).
19. Fenner, A. E. *et al.* The carbon footprint of buildings: A review of methodologies and applications. *Renew. Sustain. Energy Rev.* **94**, 1142–1152 (2018).
20. Moncaster, A. M. & Song, J.-Y. A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings. *Int. J. Sustain. Build. Technol. Urban Dev.* **3**, 26–36 (2012).
21. Nwodo, M. N. & Anumba, C. J. A review of life cycle assessment of buildings using a systematic approach. *Build. Environ.* **162**, 106290 (2019).
22. Takano, A., Winter, S., Hughes, M. & Linkosalmi, L. Comparison of life cycle assessment databases: A case study on building assessment. *Build. Environ.* **79**, 20–30 (2014).
23. Lasvaux, S., Habert, G., Peuportier, B. & Chevalier, J. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. *Int.*

J. Life Cycle Assess. **20**, 1473–1490 (2015).

24. Sinha, R., Lennartsson, M. & Frostell, B. Environmental footprint assessment of building structures: A comparative study. *Build. Environ.* **104**, 162–171 (2016).
25. Speck, R., Selke, S., Auras, R. & Fitzsimmons, J. Life Cycle Assessment Software: Selection Can Impact Results. *J. Ind. Ecol.* **20**, 18–28 (2016).
26. Emami, N. *et al.* A Life Cycle Assessment of Two Residential Buildings Using Two Different LCA Database-Software Combinations: Recognizing Uniformities and Inconsistencies. *Buildings* **9**, 20 (2019).
27. Mohebbi, G., Bahadori-Jahromi, A., Ferri, M. & Mylona, A. The Role of Embodied Carbon Databases in the Accuracy of Life Cycle Assessment (LCA) Calculations for the Embodied Carbon of Buildings. *Sustainability* **13**, 7988 (2021).
28. Teng, Y., Pan, W. & Li, K. Comparing Life Cycle Assessment Databases for Estimating Carbon Emissions of Prefabricated Buildings. in *Construction Research Congress 2018* 358–367 (American Society of Civil Engineers, 2018). doi:10.1061/9780784481301.036.
29. Pauer, E., Wohner, B. & Tacker, M. The Influence of Database Selection on Environmental Impact Results. Life Cycle Assessment of Packaging Using GaBi, Ecoinvent 3.6, and the Environmental Footprint Database. *Sustainability* **12**, 9948 (2020).
30. Richardson, S. Embodied Carbon Assessment and Decision Making Under Uncertainty: Case studies of UK supermarket construction. (University of Reading, 2017).
31. Heijungs, R. & Huijbregts, M. A. J. A Review of Approaches to Treat Uncertainty in LCA. in 8 (2004).
32. van der Sluijs, J. *et al.* Uncertainty assessment of the IMAGE/TIMER B1 CO2 emissions scenario, using the NUSAP method. 76 (2004).
33. ISO 14044 Environmental management - life cycle assessment - requirements and guidelines. (2006).

34. EN BS 15978 Sustainability of construction works-assessment of environmental performance of buildings-calculation method. (2011).
35. ISO 14025 Environmental labels and declarations, type III - environmental declarations - principles and procedures. (2006).
36. ISO 21930:2017 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services. (2017).
37. EN BS 15804 Sustainability of construction works - environmental product declarations - core rules for the product category of construction products. (2012).
38. Del Rosario, P., Palumbo, E. & Traverso, M. Environmental Product Declarations as Data Source for the Environmental Assessment of Buildings in the Context of Level(s) and DGNB: How Feasible Is Their Adoption? *Sustainability* **13**, 6143 (2021).

Appendix A - Reported Functional Units



Appendix B - Original Categories

ICE	EC3	EC3. cont.	EC3. cont.	OBD	OBD cont.	OBD cont.	OBD cont.	OBD cont.
AggregateSand 10	Accessories >> Blanket Facing 8	Finishes >> Tiling 59	Steel >> Prefab Assemb. >> Stairs 2	Building service engineering' / 'Air conditioning and ventilation' / 'Accessory' 4	Coverings' / 'Facade paint' / 'Silicate dispersion' 5	Metals' / 'Copper' / 'Cast or forged copper and brass items' 8	Mineral building products' / 'Concrete aggregates' / 'Pumice' 4	Plastics' / 'Sealing materials' / 'Silicone' 5
Aluminium 21	Accessories >> Doors Hardware 97	Finishes >> Wall Finishes 88	Steel >> Rebar 183	Building service engineering' / 'Air conditioning and ventilation' / 'Air conditioning/cooling machines' 5	Coverings' / 'Facade paint' / 'Silicone resin' 6	Metals' / 'Copper' / 'Copper sheets' 25	Mineral building products' / 'Concrete aggregates' / 'Sand and gravel' 20	Plastics' / 'Tubes' / 'Rainwater/Grey water tubes' 5
Asphalt 18	Accessories >> Flooring Accessories 2	Fire and Smoke Protection 3	Steel >> Steel Suspension Assemblies 26	Building service engineering' / 'Air conditioning and ventilation' / 'Refrigerants' 29	Coverings' / 'Fire protection' / 'Interior and exterior coatings' 1	Metals' / 'Lead' / 'Lead sheets' 4	Mineral building products' / 'Mortar and Concrete' / 'Adhesive and adhesive mortar' 8	Plastics' / 'Tubes' / 'Sewer tube' 0
Bitumen 3	Accessories >> Mortar 73	Fire and Smoke Protection >> Applied Fireproofing 17	Steel >> Structural Steel 9	Building service engineering' / 'Air conditioning and ventilation' / 'Ventilation system' 91	Coverings' / 'Interior covering' / 'Interior paint' 8	Metals' / 'Stainless steel' / 'Fastener' 10	Mineral building products' / 'Mortar and Concrete' / 'Mortar (masonry)' 30	Plastics' / 'Tubes' / 'Tab water tubes' 20
Cement 46	Accessories >> Tile Grout 18	Fire and Smoke Protection >> Firestopping 1	Steel >> Structural Steel >> Hollow Sections 38	Building service engineering' / 'Conveyance' / 'Elevator' 9	Coverings' / 'Interior covering' / 'Wall and ceiling covering' 0	Metals' / 'Stainless steel' / 'Stainless steel profiles' 5	Mineral building products' / 'Mortar and Concrete' / 'Ready mixed concrete' 80	Wood' / 'Derived timber products' / '3- and 5-ply wood' 15
Clay 16	Accessories >> Wall Base 3	Furnishings 347	Steel >> Structural Steel >> Hot-Rolled Sections 120	Building service engineering' / 'Conveyance' / 'Escalator' 9	Coverings' / 'Primer' / 'Primer for paints and plasters' 14	Metals' / 'Stainless steel sheets' 7	Mineral building products' / 'Mortar and Concrete' / 'Renders and plasters' 80	Wood' / 'Derived timber products' / 'Laminated Veneer Lumber (LVL)' 14
Concrete 309	Aggregates 270	Grouting 86	Steel >> Structural Steel >> Plate 21	Building service engineering' / 'Electrical' / 'Batteries' 5	Coverings' / 'Varnishes and stains' / 'Parquet varnish' 10	Metals' / 'Stainless steel' / 'Stainless steel tap water tubes' 4	Mineral building products' / 'Mortar and Concrete' / 'Screed dry mortar' 22	Wood' / 'Derived timber products' / 'Oriented strand board' 15
Glass 50	Air Barriers 1	Manufacturing Inputs 4	Steel >> Wire & Mesh 13	Building service engineering' / 'Electrical' / 'Cable' 16	Coverings' / 'Varnishes and stains' / 'Varnish systems for metals' 15	Metals' / 'Steel and iron' / 'Cast or forged steel and iron items' 12	Others' / '9.99 (missing translation)' / '9.99.01 (missing translation)' 0	Wood' / 'Derived timber products' / 'Particle boards' 47
Steel 18	Aluminium 22	Manufacturing Inputs >> Admixtures 5	Thermal/Moisture Prot. 9	Building service engineering' / 'Electrical' / 'Lighting' 73	Coverings' / 'Varnishes and stains' / 'Varnish systems for wooden facade' 12	Metals' / 'Steel and iron' / 'Fixing material' 5	Others' / 'Energy carrier - delivery free user' / 'Biogas' 0	Wood' / 'Derived timber products' / 'Plywood' 13
Timber 40	Aluminium >> Aluminium Suspension Assemblies 1	Manufacturing Inputs >> Carpet Fiber 23	Thermal/Moisture Prot. >> Dampproofing And Waterproofing 25	Building service engineering' / 'Electrical' / 'Switches and sockets' 13	Coverings' / 'Varnishes and stains' / 'Varnish systems for wooden windows' 18	Metals' / 'Steel and iron' / 'Steel reinforcement mesh' 3	Others' / 'Energy carrier - delivery free user' / 'District heat' 8	Wood' / 'Derived timber products' / 'Veneer layer wood' 5
	Aluminium >> Billets 21	Manufacturing Inputs >> Cementitious 1	Thermal/Moisture Prot. >> Insulation 77	Building service engineering' / 'Heating' / 'Heat distribution and dissipation' 54	End of Life' / 'Generic' / 'Building service engineering' 8	Metals' / 'Steel and iron' / 'Steel sheets' 33	Others' / 'Energy carrier - delivery free user' / 'Drinking water' 1	Wood' / 'Derived timber products' / 'Wood cement boards' 32
	Aluminium >> Extrusions 76	Manufacturing Inputs >> Cementitious >> Cement 277	Thermal/Moisture Prot. >> Insulation >> Blanket 379	Building service engineering' / 'Heating' / 'Heat generator' 201	End of Life' / 'Generic' / 'Construction waste' 3	Metals' / 'Steel and iron' / 'Structural steel profile' 75	Others' / 'Energy carrier - delivery free user' / 'Electricity' 30	Wood' / 'Derived timber products' / 'Wood fibre boards' 19
	Aluminium >> Sheet 31	Manufacturing Inputs >> Cementitious >> SCM 12	Thermal/Moisture Prot. >> Insulation >> Blown 74	Building service engineering' / 'Heating' / 'Storage' 93	End of Life' / 'Generic' / 'Consumer waste' 3	Metals' / 'Surface treatment and coating of metals' / '(Wet) varnishing of metals' 10	Others' / 'Energy carrier - delivery free user' / 'Fuel from vegetable oil' 0	Wood' / 'End-of-life processes' / 'EoL OSB' 0
	Asphalt 110	Manufacturing Inputs >> Glass Panes 274	Thermal/Moisture Prot. >> Insulation >> Board 452	Building service engineering' / 'Sanitary' / 'Sanitary ware' 7	End of Life' / 'Generic' / 'Metals' 8	Metals' / 'Surface treatment and coating of metals' / 'Anodising of aluminium' 1	Others' / 'Energy carrier - delivery free user' / 'Heating oil' 3	Wood' / 'End-of-life processes' / 'EoL particle boards' 0
	Cast Decks and Underlayment 55	Manufacturing Inputs >> Textiles 13	Thermal/Moisture Prot. >> Insulation >> Foamed-In-Place 23	Building service engineering' / 'Sanitary' / 'Shower and bath tubs' 11	End of Life' / 'Generic' / 'Plastics' 6	Metals' / 'Surface treatment and coating of metals' / 'Powder coating' 5	Others' / 'Energy carrier - delivery free user' / 'Liquid gas' 1	Wood' / 'Solid wood' / 'Duo and trio laminated beams' 8
	Cladding 41	Masonry 11	Thermal/Moisture Prot. >> Insulation >> Sprayed 43	Building service engineering' / 'Use' / 'Use conveyor' 3	End of Life' / 'Generic' / 'Wood' 4	Metals' / 'Zinc' / 'Zinc sheets' 8	Others' / 'Energy carrier - delivery free user' / 'Natural gas' 1	Wood' / 'Solid wood' / 'Glue-laminated timber board' 37
	Cladding >> Insulated Roof Panels 18	Masonry >> Brick 154	Thermal/Moisture Prot. >> Joint Protection 2	Building service engineering' / 'Use' / 'Use heat generator (EnEV)' 31	Insulation materials' / 'Calcium silicate / Calcium-' / 'Calcium silicate' 5	Mineral building products' / 'Asphalt' / 'Asphalt binder' 6	Others' / 'Energy carrier - delivery free user' / 'Wood pellets' 1	Wood' / 'Solid wood' / 'Glue-laminated timber' 30
	Cladding >> Insulated Wall Panels 75	Mechanical Insulation 96	Thermal/Moisture Prot. >> Membrane Roofing 3	Building service engineering' / 'Use' / 'Use heat generator' 38	Insulation materials' / 'Cellulose fibre' / 'Cellulose insulation (loose fill)' 19	Mineral building products' / 'Asphalt' / 'Base courses' 12	Others' / 'Passenger transport [person km]' / 'Passenger car' 4	Wood' / 'Solid wood' / 'Solid structural timber (KVH)' 8
	Cladding >> Roof Panels 50	Openings 10	Thermal/Moisture Prot. >> Membrane Roofing >> Bituminous 59	Building service engineering' / 'Use' / 'Use lighting' 1	Insulation materials' / 'Cellulose fibre' / 'Cellulose insulation (panels)' 5	Mineral building products' / 'Asphalt' / 'Mastic asphalt' 10	Others' / 'Processes at building site' / 'Concreting' 1	Wood' / 'Solid wood' / 'Structural timber' 32
	Cladding >> Siding 39	Openings >> Curtain Walls 25	Thermal/Moisture Prot. >> Membrane Roofing >> EPDM 14	Building service engineering' / 'Use' / 'Use ventilation and air conitioning' 4	Insulation materials' / 'Cotton' / 'Conventional Cotton' 5	Mineral building products' / 'Asphalt' / 'Split mastic asphalt' 6	Others' / 'Processes at building site' / 'Digger/digging' 2	Wood' / 'Wooden floor' / 'Cork' 24
	Cladding >> Stone Cladding 25	Openings >> Glazing (IGU) 139	Thermal/Moisture Prot. >> Membrane Roofing >> KEE 16	Components for windows and curtain walls' / 'Accessories for windows, walling and doors' / 'Fire resistance and smoke control devices' 26	Insulation materials' / 'Cotton' / 'Organic cotton' 5	Mineral building products' / 'Binder' / 'Cement' 11	Others' / 'Transport of goods [t km]' / 'Inland water transport' 1	Wood' / 'Wooden floor' / 'Laminate flooring' 9
	Cladding >> Wall Panels 55	Openings >> Glazing (IGU) >> Mirrors 2	Thermal/Moisture Prot. >> Membrane Roofing >> Other 34	Components for windows and curtain walls' / 'Accessories for windows, walling and doors' / 'Solar protection devices' 65	Insulation materials' / 'Expanded cork' / 'Expanded cork' 5	Mineral building products' / 'Binder' / 'Clay' 4	Others' / 'Transport of goods [t km]' / 'Ocean transport' 3	Wood' / 'Wooden floor' / 'Multilayer Modular Floor Coverings' 6
	Concrete >> Flowable Fill (CDF) 2107	Openings >> Storefronts 15	Thermal/Moisture Prot. >> Membrane Roofing >> PVC 104	Components for windows and curtain walls' / 'Daylight systems and smoke/heat control systems' / 'Roof lights' 81	Insulation materials' / 'Expanded perlit' / 'Panels' 5	Mineral building products' / 'Binder' / 'Gypsum' 9	Others' / 'Transport of goods [t km]' / 'Train' 1	Wood' / 'Wooden floor' / 'Parquet' 34
	Concrete >> High Strength Cement-Based Grout 793	Openings >> Translucent Wall and Roof Assemblies 3	Thermal/Moisture Prot. >> Membrane Roofing >> Polyurethane 2	Components for windows and curtain walls' / 'Daylight systems and smoke/heat control systems' / 'Smoke and heat control systems' 54	Insulation materials' / 'Expanded polystyrene' / 'EPS grey' 12	Mineral building products' / 'Binder' / 'Lime' 2	Others' / 'Transport of goods [t km]' / 'Truck' 4	
	Concrete >> Paving 226	Openings >> Window Wall Assemblies 8	Thermal/Moisture Prot. >> Membrane Roofing >> TPO 28	Components for windows and curtain walls' / 'Doors' / 'Aluminium' 145	Insulation materials' / 'Expanded polystyrene' / 'EPS white' 10	Mineral building products' / 'Bricks, blocks and elements' / 'Aerated concrete' 22	Plastics' / 'Elastic plastic profiles' / 'Resin-composite facade panels' 5	
	Concrete >> ReadyMix 72965	Openings >> Windows 85	Thermal/Moisture Prot. >> Steep Slope Roofing 9	Components for windows and curtain walls' / 'Doors' / 'Steel' 280	Insulation materials' / 'Extruded polystyrene' / 'XPS white' 34	Mineral building products' / 'Bricks, blocks and elements' / 'Air-dried brick (adobe)' 13	Plastics' / 'Elastic plastic profiles' / 'Transparent panels' 20	
	Concrete >> Shotcrete 1766	OtherMaterials 12	Thermal/Moisture Prot. >> Weather Barriers 5	Components for windows and curtain walls' / 'Drive system' / 'electrical' 38	Insulation materials' / 'Flax fibre' / 'Flax fibre mat' 5	Mineral building products' / 'Bricks, blocks and elements' / 'Artificial stone' 6	Plastics' / 'Floorings' / 'Linoleum flooring' 19	
	Concrete Unit Masonry 216	OtherMaterials >> Copper 6	Wood 46	Components for windows and curtain walls' / 'Frames / Profiles' / 'Aluminium thermally separated' 103	Insulation materials' / 'Foam glass' / 'Panels' 7	Mineral building products' / 'Bricks, blocks and elements' / 'Ceiling panel' 4	Plastics' / 'Floorings' / 'PVC flooring' 59	

	Data Cabling 584	OtherMaterials >> Gypsum Finishing Compounds 25	Wood >> Composite Lumber 18	Components for windows and curtain walls' / 'Frames / Profiles' / 'Aluminium' 15	Insulation materials' / 'Hemp' / 'Hemp fibre mat' 5	Mineral building products' / 'Bricks, blocks and elements' / 'Ceramic roof tile' 24	Plastics' / 'Floorings' / 'Rubber flooring' 35	
	Doors and Frames 57	OtherMaterials >> Piping 137	Wood >> Dimension Lumber 2	Components for windows and curtain walls' / 'Frames / Profiles' / 'PVC' 10	Insulation materials' / 'Insulation elements' / 'Isokorb thermal breaks' 6	Mineral building products' / 'Bricks, blocks and elements' / 'Concrete roof tiles' 13	Plastics' / 'Floorings' / 'Textile flooring' 50	
	Doors and Frames >> Metal Doors and Frames 62	OtherMaterials >> Profiles 30	Wood >> Dimension Lumber >> Wood Decking 3	Components for windows and curtain walls' / 'Frames / Profiles' / 'Steel' 61	Insulation materials' / 'Insulation foam' / 'mineral' 7	Mineral building products' / 'Bricks, blocks and elements' / 'Dry screed' 7	Plastics' / 'Floorings' / 'Thermoplastic / Polyolefine flooring' 20	
	Doors and Frames >> Specialty Doors and Frames 7	OtherMaterials >> Transportation Infrastructure 27	Wood >> Dimension Lumber >> Wood Framing 7	Components for windows and curtain walls' / 'Frames / Profiles' / 'Wood' 10	Insulation materials' / 'Melamine resin' / 'Melamine foam' 5	Mineral building products' / 'Bricks, blocks and elements' / 'Fibre Cement' 9	Plastics' / 'Foils and fleeces' / 'Building papers' 5	
	Doors and Frames >> Specialty Doors and Frames >> Sliding Glass Doors 10	OtherMaterials >> Transportation Infrastructure >> Auxiliaries 2	Wood >> Heavy Timber 2	Components for windows and curtain walls' / 'Infill' / 'Opaque fillings' 16	Insulation materials' / 'Mineral wool' / 'Glass wool' 21	Mineral building products' / 'Bricks, blocks and elements' / 'Fired brick' 67	Plastics' / 'Foils and fleeces' / 'Fleeces' 9	
	Doors and Frames >> Wood Doors 28	OtherMaterials >> Unknown 156	Wood >> Mass Timber 57	Components for windows and curtain walls' / 'Infill' / 'Transparent infill' 140	Insulation materials' / 'Mineral wool' / 'Mineral wool' 42	Mineral building products' / 'Bricks, blocks and elements' / 'Glass block' 3	Plastics' / 'Foils and fleeces' / 'Sealing foils' 46	
	Electricity 1	OtherMaterials >> Unsupported 416	Wood >> Non-Structural Wood 51	Components for windows and curtain walls' / 'Sealing components / materials' / 'Joint sealing tapes' 20	Insulation materials' / 'Mineral wool' / 'Rock wool' 35	Mineral building products' / 'Bricks, blocks and elements' / 'Gypsum plasterboard' 348	Plastics' / 'Foils and fleeces' / 'Secondary water-shedding membrane' 26	
	Finishes 41	OtherMaterials >> Unsupported >> Cleaning Products 1	Wood >> Plywood and OSB Sheathing Panels 78	Components for windows and curtain walls' / 'Sealing components / materials' / 'Rubber seal' 15	Insulation materials' / 'Polyethylene' / 'Foam' 25	Mineral building products' / 'Bricks, blocks and elements' / 'Light concrete' 34	Plastics' / 'Foils and fleeces' / 'Technical textiles' 41	
	Finishes >> Backing&Underlay 4	OtherMaterials >> Unsupported >> Clothing 61	Wood >> Prefabricated Wood Products 1	Components for windows and curtain walls' / 'Sealing components / materials' / 'Sealing profiles' 50	Insulation materials' / 'Polyurethane rigid foam' / 'PIR rigid foam' 5	Mineral building products' / 'Bricks, blocks and elements' / 'Natural cut stone' 36	Plastics' / 'Foils and fleeces' / 'Vapour barriers and brakes' 15	
	Finishes >> Ceiling Panels 207	OtherMaterials >> Unsupported >> Food Beverage 137	Wood >> Prefabricated Wood Products >> Prefabricated Truss 1	Components for windows and curtain walls' / 'Walling' / 'Curtain walling - stick construction' 28	Insulation materials' / 'Polyurethane rigid foam' / 'PU slabstock foam' 7	Mineral building products' / 'Bricks, blocks and elements' / 'Precast concrete elements and goods' 350	Plastics' / 'Profiles' / 'Elastic plastic profiles' 20	
	Finishes >> Ceiling Panels >> Acoustical Ceilings 412	OtherMaterials >> Zinc 8	Wood >> Unfinished 2	Components for windows and curtain walls' / 'Walling' / 'Curtain walling - unitized walling' 28	Insulation materials' / 'Rigid phenolic foam' / 'Phenolic foam boards' 8	Mineral building products' / 'Bricks, blocks and elements' / 'Sand lime brick' 7	Plastics' / 'Profiles' / 'Rigid plastic profiles ' 20	
	Finishes >> Cement Board 30	Precast Concrete 209	Wood I-Joists 5	Components for windows and curtain walls' / 'Walling' / 'Other walling' 15	Insulation materials' / 'Rubber' / 'Foam' 0	Mineral building products' / 'Bricks, blocks and elements' / 'Slate' 5	Plastics' / 'Roofing membranes' / 'Bituminous sheet' 26	
	Finishes >> Decking Boards 10	Sheathing >> Cement Sheathing 3		Components for windows and curtain walls' / 'Window fittings' / 'Aluminium window fittings' 16	Insulation materials' / 'Straw' / 'Straw bale' 15	Mineral building products' / 'Bricks, blocks and elements' / 'Stoneware' 10	Plastics' / 'Roofing membranes' / 'ECB roofing membrane (Ethylene Copolymer Bitumen)' 5	
	Finishes >> Flooring 7	Sheathing >> Gypsum Sheathing 16		Components for windows and curtain walls' / 'Window fittings' / 'Fastening materials' 8	Insulation materials' / 'Thermal insulation composite system' / 'Thermal insulation composite system' 48	Mineral building products' / 'Bricks, blocks and elements' / 'Substrate' 5	Plastics' / 'Roofing membranes' / 'EVA sheet (Ehylene Vinyl Acetate)' 17	
	Finishes >> Flooring >> Access Flooring 76	Steel 73		Components for windows and curtain walls' / 'Window fittings' / 'Steel window fittings' 4	Insulation materials' / 'Urea formaldehyde resin' / 'Urea-formaldehyde foam insulation (UFFI)' 5	Mineral building products' / 'Bricks, blocks and elements' / 'Tiles and cladding panels' 48	Plastics' / 'Roofing membranes' / 'Elastomer sheet' 42	
	Finishes >> Flooring >> Carpet 763	Steel >> Coil 20		Components for windows and curtain walls' / 'Window fittings' / 'Window handles' 5	Insulation materials' / 'Wood fibre' / 'Wood fibre and wood chips, loose' 22	Mineral building products' / 'Concrete aggregates' / 'Byproducts from power plant' 3	Plastics' / 'Roofing membranes' / 'PVC sheet' 15	
	Finishes >> Flooring >> Laminate 13	Steel >> Cold Formed 185		Components for windows and curtain walls' / 'Windows' / 'Metal windows' 72	Insulation materials' / 'Wood fibre' / 'Wood fibre insulation boards' 73	Mineral building products' / 'Concrete aggregates' / 'Dry filling material' 7	Plastics' / 'Roofing membranes' / 'TPO roofing membranes' 48	
	Finishes >> Flooring >> Other Flooring 136	Steel >> Decking 22		Composites' / 'System components' / 'Ceilings ' 47	Insulation materials' / 'Wood wool panels' / 'Wood wool panels' 5	Mineral building products' / 'Concrete aggregates' / 'Expanded clay' 2	Plastics' / 'Sealing materials' / 'Acrylate' 0	
	Finishes >> Flooring >> Resilient Flooring 433	Steel >> Merchant Bar 25		Composites' / 'System components' / 'Flooring' 5	Metals' / 'Aluminium' / 'Aluminium foil' 0	Mineral building products' / 'Concrete aggregates' / 'Expanded shale' 1	Plastics' / 'Sealing materials' / 'Bitumen' 8	
	Finishes >> Flooring >> Wood Flooring 74	Steel >> Post-Tensioning 9		Composites' / 'System components' / 'Inner walls' 39	Metals' / 'Aluminium' / 'Aluminium profiles' 9	Mineral building products' / 'Concrete aggregates' / 'Granulated foam glass' 1	Plastics' / 'Sealing materials' / 'PVC' 5	
	Finishes >> Gypsum Board 485	Steel >> Prefab Assemb. >> Misc. 3		Composites' / 'System components' / 'Outer walls' 18	Metals' / 'Aluminium' / 'Aluminium sheets' 0	Mineral building products' / 'Concrete aggregates' / 'Natural stone' 30	Plastics' / 'Sealing materials' / 'Polyurethane' 5	
	Finishes >> Painting and Coating 498	Steel >> Prefab Assemb. >> Railings 1		Coverings' / 'Facade paint' / 'Dispersion' 6	Metals' / 'Aluminium' / 'Cast aluminium' 0	Mineral building products' / 'Concrete aggregates' / 'Perlite' 2	Plastics' / 'Sealing materials' / 'Rubber' 5	

Appendix C - Common Material Categories and Re-categorization

ICE Original	ICE Recategorization	EC3 Original	EC3 Re-categorization	OBD original	OBD Re-categorization
Aluminium 21	Aluminium	Aluminium 22	Aluminium	Components for windows and curtain walls' / 'Infill' / 'Transparent infill' 140	Glass/Glazing
Asphalt 18	Asphalt	Aluminium >> Aluminium Suspension Assemblies 1	Aluminium	Metals' / 'Aluminium' / 'Aluminium foil' 0	Aluminium
Cement 46	Cement	Aluminium >> Billets 21	Aluminium	Metals' / 'Aluminium' / 'Aluminium profiles' 9	Aluminium
Concrete 309	Concrete	Aluminium >> Extrusions 76	Aluminium	Metals' / 'Aluminium' / 'Aluminium sheets' 0	Aluminium
Glass 50	Glass/Glazing	Aluminium >> Sheet 31	Aluminium	Metals' / 'Aluminium' / 'Cast aluminium' 0	Aluminium
Steel 18	Steel	Asphalt 110	Asphalt	Metals' / 'Stainless steel' / 'Fastener' 10	Steel
Timber 40	Wood	Concrete >> Flowable Fill (CDF) 2107	Concrete	Metals' / 'Stainless steel' / 'Stainless steel profiles' 5	Steel
		Concrete >> High Strength Cement-Based Grout 793	Concrete	Metals' / 'Stainless steel' / 'Stainless steel sheets' 7	Steel
		Concrete >> Paving 226	Concrete	Metals' / 'Stainless steel' / 'Stainless steel tap water tubes' 4	Steel
		Concrete >> ReadyMix 72965	Concrete	Metals' / 'Steel and iron' / 'Cast or forged steel and iron items' 12	Steel
		Concrete >> Shotcrete 1766	Concrete	Metals' / 'Steel and iron' / 'Fixing material' 5	Steel
		Concrete Unit Masonry 216	Concrete	Metals' / 'Steel and iron' / 'Steel reinforcement mesh' 3	Steel
		Manufacturing Inputs >> Cementitious 1	Cement	Metals' / 'Steel and iron' / 'Steel sheets' 33	Steel
		Manufacturing Inputs >> Cementitious >> Cement 277	Cement	Metals' / 'Steel and iron' / 'Structural steel profile' 75	Steel
		Manufacturing Inputs >> Cementitious >> SCM 12	Cement	Mineral building products' / 'Asphalt' / 'Asphalt binder' 6	Asphalt
		Manufacturing Inputs >> Glass Panes 274	Glass/Glazing	Mineral building products' / 'Asphalt' / 'Base courses' 12	Asphalt
		Openings >> Glazing (IGU) 139	Glass/Glazing	Mineral building products' / 'Asphalt' / 'Mastic asphalt' 10	Asphalt
		Precast Concrete 209	Concrete	Mineral building products' / 'Asphalt' / 'Split mastic asphalt' 6	Asphalt
		Steel 73	Steel	Mineral building products' / 'Binder' / 'Cement' 11	Cement
		Steel >> Coil 20	Steel	Mineral building products' / 'Bricks, blocks and elements' / 'Aerated concrete' 22	Concrete
		Steel >> Cold Formed 185	Steel	Mineral building products' / 'Bricks, blocks and elements' / 'Concrete roof tiles' 13	Concrete
		Steel >> Decking 22	Steel	Mineral building products' / 'Bricks, blocks and elements' / 'Precast concrete elements and goods' 350	Concrete
		Steel >> Merchant Bar 25	Steel	Mineral building products' / 'Mortar and Concrete' / 'Ready mixed concrete' 80	Concrete
		Steel >> Post-Tensioning 9	Steel	Wood' / 'Derived timber products' / '3- and 5-ply wood' 15	Wood
		Steel >> Prefab Assemb. >> Misc. 3	Steel	Wood' / 'Derived timber products' / 'Laminated Veneer Lumber (LVL)' 14	Wood
		Steel >> Prefab Assemb. >> Railings 1	Steel	Wood' / 'Derived timber products' / 'Oriented strand board' 15	Wood
		Steel >> Prefab Assemb. >> Stairs 2	Steel	Wood' / 'Derived timber products' / 'Particle boards' 47	Wood
		Steel >> Rebar 183	Steel	Wood' / 'Derived timber products' / 'Plywood' 13	Wood
		Steel >> Steel Suspension Assemblies 26	Steel	Wood' / 'Derived timber products' / 'Veneer layer wood' 5	Wood

		Steel >> Structural Steel 9	Steel	Wood' / 'Derived timber products' / 'Wood cement boards' 32	Wood
		Steel >> Structural Steel >> Hollow Sections 38	Steel	Wood' / 'Derived timber products' / 'Wood fibre boards' 19	Wood
		Steel >> Structural Steel >> Hot-Rolled Sections 120	Steel	Wood' / 'End-of-life processes' / 'EoL OSB' 0	Wood
		Steel >> Structural Steel >> Plate 21	Steel	Wood' / 'End-of-life processes' / 'EoL particle boards' 0	Wood
		Steel >> Wire & Mesh 13	Steel	Wood' / 'Solid wood' / 'Duo and trio laminated beams' 8	Wood
		Wood 46	Wood	Wood' / 'Solid wood' / 'Glue-laminated timber board' 37	Wood
		Wood >> Composite Lumber 18	Wood	Wood' / 'Solid wood' / 'Glue-laminated timber' 30	Wood
		Wood >> Dimension Lumber 2	Wood	Wood' / 'Solid wood' / 'Solid structural timber (KVH)' 8	Wood
		Wood >> Dimension Lumber >> Wood Decking 3	Wood	Wood' / 'Solid wood' / 'Structural timber' 32	Wood
		Wood >> Dimension Lumber >> Wood Framing 7	Wood	Wood' / 'Wooden floor' / 'Cork' 24	Wood
		Wood >> Heavy Timber 2	Wood	Wood' / 'Wooden floor' / 'Laminate flooring' 9	Wood
		Wood >> Mass Timber 57	Wood	Wood' / 'Wooden floor' / 'Multilayer Modular Floor Coverings' 6	Wood
		Wood >> Non-Structural Wood 51	Wood	Wood' / 'Wooden floor' / 'Parquet' 34	Wood
		Wood >> Plywood and OSB Sheathing Panels 78	Wood		
		Wood >> Prefabricated Wood Products 1	Wood		
		Wood >> Prefabricated Wood Products >> Prefabricated Truss 1	Wood		
		Wood >> Unfinished 2	Wood		
		Wood I-Joists 5	Wood		

Appendix D - Common Material Statistical Values LCA Stages A1-A3

Aluminium	EC3	ICE	OBD
Max	20.800	6.669	10.680
Min	-0.402	0.266	8.460
Median	8.800	1.123	8.589
Mean	8.185	1.501	9.243
Standard Deviation	4.141	1.411	1.246
Q1	5.900	0.721	8.525
Q3	10.102	1.721	9.635
Interquartile Range	4.202	1.000	1.110
Mean + Standard Deviation	12.326	2.912	10.489
Mean - Standard Deviation	4.045	0.090	7.997

Asphalt	EC3	ICE	OBD
Max	0.124	0.058	0.117
Min	0.004	0.050	0.071
Median	0.054	0.054	0.078
Mean	0.053	0.054	0.086
Standard Deviation	0.023	0.003	0.017
Q1	0.035	0.052	0.077
Q3	0.067	0.056	0.093
Interquartile Range	0.032	0.004	0.016
Mean + Standard Deviation	0.077	0.057	0.104
Mean - Standard Deviation	0.030	0.051	0.069

Cement	EC3	ICE	OBD
Max	1.209	2.670	587.000
Min	0.032	0.000	0.378
Median	0.742	0.594	0.783
Mean	0.693	0.621	79.465
Standard Deviation	0.251	0.585	188.168
Q1	0.601	0.153	0.682
Q3	0.848	0.798	0.843
Interquartile Range	0.247	0.645	0.162
Mean + Standard Deviation	0.944	1.206	267.633
Mean - Standard Deviation	0.442	0.036	-108.703

Concrete	EC3	ICE	OBD
Max	162.329	0.280	244.000
Min	0.011	0.026	-0.705
Median	0.153	0.098	0.121
Mean	0.162	0.105	36.951
Standard Deviation	0.930	0.047	81.082
Q1	0.127	0.073	-0.549
Q3	0.182	0.126	0.437
Interquartile Range	0.055	0.053	0.986
Mean + Standard Deviation	1.092	0.152	118.033
Mean - Standard Deviation	-0.768	0.058	-44.131

Glass/Glazing	EC3	ICE	OBD
Max	491.000	3.102	5.286
Min	0.693	1.437	-1.307
Median	1.560	1.646	1.449
Mean	4.412	1.686	1.878
Standard Deviation	30.885	0.281	1.286
Q1	1.297	1.556	1.166
Q3	2.301	1.747	2.814
Interquartile Range	1.005	0.192	1.648
Mean + Standard Deviation	35.297	1.967	3.165
Mean - Standard Deviation	-26.473	1.405	0.592

Steel	EC3	ICE	OBD
Max	11.700	3.834	3387.000
Min	0.107	0.730	0.683
Median	1.060	2.495	2.504
Mean	1.563	2.375	329.532
Standard Deviation	1.149	0.647	876.001
Q1	0.755	2.165	1.770
Q3	2.380	2.833	3.006
Interquartile Range	1.625	0.668	1.235
Mean + Standard Deviation	2.712	3.022	1205.533
Mean - Standard Deviation	0.414	1.728	-546.469

Wood	EC3	ICE	OBD
Max	4.400	1.440	1.412
Min	-1.449	-0.580	-1.691
Median	0.446	0.284	-1.170
Mean	0.534	-0.170	-1.025
Standard Deviation	0.729	0.839	0.582
Q1	0.216	-1.035	-1.409
Q3	0.705	0.506	-0.872
Interquartile Range	0.489	1.541	0.538
Mean + Standard Deviation	1.263	0.669	-0.443
Mean - Standard Deviation	-0.195	-1.008	-1.607

Appendix E - EIOD - GWP by Materials in kgCO2/kg of materials

Material	A1_A3_Mean	A1_A3_Median	A1_A3_Min	A1_A3_Max	A1_A3_Q1	A1_A3_Q3	A1_A3_Sd	A1_A3_DB	A1_A3_Count
Aluminium	6.53	6.37	0.27	20.80	1.80	9.83	4.59	['EC3' 'ICE' 'OBD']	83
Asphalt	0.06	0.05	0.00	0.12	0.04	0.07	0.02	['EC3' 'ICE' 'OBD']	88
Brick	2.12	0.40	0.16	255.55	0.37	0.42	20.90	['EC3' 'ICE' 'OBD']	148
Cement	4.51	0.71	0.00	587.00	0.53	0.84	43.06	['EC3' 'ICE' 'OBD']	226
Concrete	0.19	0.15	-0.71	244.00	0.13	0.18	2.58	['EC3' 'ICE' 'OBD']	75541
Glass/Glazing	3.95	1.58	0.06	491.00	1.30	2.21	28.04	['EC3' 'ICE' 'OBD']	412
Gypsum	0.46	0.27	0.00	21.70	0.19	0.32	1.82	['EC3' 'OBD']	422
Insulation	2.96	1.31	-1.63	95.18	0.98	2.55	8.18	['EC3' 'OBD']	817
Membrane	2.68	2.84	0.00	8.84	1.66	3.38	1.49	['EC3' 'OBD']	211
Paint	7.95	2.47	0.10	184.50	1.87	4.07	19.73	['EC3' 'OBD']	280
Steel	26.53	1.22	0.11	3387.00	0.79	2.42	253.88	['EC3' 'ICE' 'OBD']	526
Wood	0.08	0.28	-1.69	4.40	-0.82	0.64	0.96	['EC3' 'ICE' 'OBD']	237

Material	A4_Mean	A4_Median	A4_Min	A4_Max	A4_Q1	A4_Q3	A4_Sd	A4_DB	A4_Count
Aluminium									0.00
Asphalt									0.00
Brick	2.51	0.01	0.01	12.50	0.01	0.01	5.00	['OBD']	5.00
Cement									0.00
Concrete	0.76	0.01	0.00	20.29	0.01	0.01	3.83	['OBD']	27.00
Glass/Glazing	0.06	0.06	0.01	0.15	0.01	0.07	0.05	['OBD']	12.00
Gypsum	0.02	0.01	0.01	0.10	0.01	0.01	0.02	['OBD']	21.00
Insulation	0.07	0.04	0.01	0.33	0.02	0.07	0.07	['OBD']	24.00
Membrane	0.03	0.03	0.02	0.05	0.02	0.05	0.01	['OBD']	15.00
Paint									0.00
Steel	0.01	0.01	0.01	0.01	0.01	0.01	0.00	['OBD']	1.00
Wood	0.04	0.02	0.01	0.15	0.01	0.05	0.04	['OBD']	14.00

Material	B2_Mean	B2_Median	B2_Min	B2_Max	B2_Q1	B2_Q3	B2_Sd	B2_DB	B2_Count
Aluminium									0
Asphalt									0
Brick	0.00	0.00	0.00	0.00	0.00	0.00	0.00	['OBD']	3
Cement									0
Concrete	0.00	0.00	0.00	0.00	0.00	0.00	0.00	['OBD']	18
Glass/Glazing									0
Gypsum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	['OBD']	21
Insulation	0.15	0.15	0.00	0.29	0.07	0.22	0.15	['OBD']	2
Membrane									0

Paint									0
Steel									0
Wood	0.04	0.01	0.00	0.14	0.00	0.05	0.06	['OBD']	4

Material	B3_Mean	B3_Median	B3_Min	B3_Max	B3_Q1	B3_Q3	B3_Sd	B3_DB	B3_Count
Aluminium									0
Asphalt									0
Brick	0	0	0	0	0	0	0	['OBD']	3
Cement									0
Concrete	0	0	0	0	0	0	0	['OBD']	18
Glass/Glazing									0
Gypsum	0	0	0	0	0	0	0	['OBD']	21
Insulation	0	0	0	0	0	0	0	['OBD']	1
Membrane									0
Paint									0
Steel									0
Wood	0	0	0	0	0	0	0	['OBD']	1

Material	B4_Mean	B4_Median	B4_Min	B4_Max	B4_Q1	B4_Q3	B4_Sd	B4_DB	B4_Count
Aluminium									0
Asphalt									0
Brick	0	0	0	0	0	0	0	['OBD']	3
Cement									0
Concrete	0	0	0	0	0	0	0	['OBD']	19
Glass/Glazing									0
Gypsum	0	0	0	0	0	0	0	['OBD']	21
Insulation	0	0	0	0	0	0	0	['OBD']	1
Membrane									0
Paint									0
Steel									0
Wood	0	0	0	0	0	0	0	['OBD']	1

Material	B4_Corrected_Mean	B4_Corrected_Median	B4_Corrected_Min	B4_Corrected_Max	B4_Corrected_Q1	B4_Corrected_Q3	B4_Corrected_Sd	B4_Corrected_DB	B4_Corrected_Count
Aluminium	6.53	6.37	0.27	20.80	1.80	9.83	4.59	['EC3' 'ICE' 'OBD']	83
Asphalt	0.06	0.05	0.00	0.12	0.04	0.07	0.02	['EC3' 'ICE' 'OBD']	88
Brick	2.12	0.40	0.16	255.55	0.37	0.42	20.90	['EC3' 'ICE' 'OBD']	148
Cement	4.51	0.71	0.00	587.00	0.53	0.84	43.06	['EC3' 'ICE' 'OBD']	226
Concrete	0.19	0.15	-0.71	244.00	0.13	0.18	2.58	['EC3' 'ICE' 'OBD']	75541
Glass/Glazing	3.95	1.58	0.06	491.00	1.30	2.21	28.04	['EC3' 'ICE' 'OBD']	412
Gypsum	0.46	0.27	0.00	21.70	0.19	0.32	1.82	['EC3' 'OBD']	422

Insulation	2.96	1.31	-1.63	95.18	0.98	2.55	8.18	['EC3' 'OBD']	817
Membrane	2.68	2.84	0.00	8.84	1.66	3.38	1.49	['EC3' 'OBD']	211
Paint	7.95	2.47	0.10	184.50	1.87	4.07	19.73	['EC3' 'OBD']	280
Steel	26.53	1.22	0.11	3387.00	0.79	2.42	253.88	['EC3' 'ICE' 'OBD']	526
Wood	0.08	0.28	-1.69	4.40	-0.82	0.64	0.96	['EC3' 'ICE' 'OBD']	237

Material	B5_Mean	B5_Median	B5_Min	B5_Max	B5_Q1	B5_Q3	B5_Sd	B5_DB	B5_Count
Aluminium									0
Asphalt									0
Brick	0	0	0	0	0	0	0	['OBD']	3
Cement									0
Concrete	0	0	0	0	0	0	0	['OBD']	19
Glass/Glazing									0
Gypsum	0	0	0	0	0	0	0	['OBD']	21
Insulation	0	0	0	0	0	0	0	['OBD']	1
Membrane									0
Paint									0
Steel									0
Wood	0	0	0	0	0	0	0	['OBD']	1

Material	C2_Mean	C2_Median	C2_Min	C2_Max	C2_Q1	C2_Q3	C2_Sd	C2_DB	C2_Count
Aluminium									0
Asphalt	0.01	0.01	0.00	0.01	0.01	0.01	0.00	['OBD']	6
Brick	0.15	0.00	0.00	1.04	0.00	0.01	0.36	['OBD']	7
Cement									0
Concrete	0.46	0.00	0.00	3.38	0.00	0.01	0.88	['OBD']	49
Glass/Glazing	0.01	0.00	0.00	0.01	0.00	0.01	0.00	['OBD']	20
Gypsum	0.00	0.00	0.00	0.03	0.00	0.00	0.00	['OBD']	29
Insulation	0.01	0.00	0.00	0.04	0.00	0.01	0.01	['OBD']	57
Membrane	0.01	0.00	0.00	0.02	0.00	0.01	0.01	['OBD']	29
Paint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	['OBD']	3
Steel	0.01	0.00	0.00	0.05	0.00	0.00	0.01	['OBD']	15
Wood	0.00	0.00	0.00	0.01	0.00	0.00	0.00	['OBD']	56

Material	C3_Mean	C3_Median	C3_Min	C3_Max	C3_Q1	C3_Q3	C3_Sd	C3_DB	C3_Count
Aluminium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	['OBD']	3
Asphalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	['OBD']	6
Brick	0.37	-0.02	-0.02	2.63	-0.02	0.01	0.92	['OBD']	7
Cement									0
Concrete	0.00	0.00	0.00	0.01	0.00	0.01	0.00	['OBD']	39
Glass/Glazing	0.52	0.01	0.00	2.82	0.00	0.06	1.08	['OBD']	22

Gypsum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	['OBD']	22
Insulation	1.95	0.03	0.00	52.51	0.00	2.20	7.26	['OBD']	51
Membrane	1.29	0.13	0.00	3.98	0.01	2.75	1.41	['OBD']	28
Paint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	['OBD']	1
Steel	0.30	0.06	0.00	2.48	0.00	0.07	0.66	['OBD']	28
Wood	1.61	1.62	0.23	2.10	1.58	1.67	0.24	['OBD']	62

Material	C4_Mean	C4_Median	C4_Min	C4_Max	C4_Q1	C4_Q3	C4_Sd	C4_DB	C4_Count
Aluminium									0
Asphalt	0.08	0.08	0.08	0.08	0.08	0.08	0.00	['OBD']	1
Brick	0.00	0.00	0.00	0.00	0.00	0.00	0.00	['OBD']	5
Cement									0
Concrete	5.34	0.82	0.00	16.07	0.81	13.83	6.41	['OBD']	32
Glass/Glazing	0.02	0.01	0.01	0.03	0.01	0.02	0.01	['OBD']	19
Gypsum	0.07	0.06	0.02	0.70	0.02	0.07	0.12	['OBD']	29
Insulation	0.44	0.02	0.00	3.33	0.01	0.07	0.96	['OBD']	39
Membrane	0.33	0.04	0.00	2.75	0.00	0.08	0.77	['OBD']	12
Paint	0.02	0.02	0.02	0.02	0.02	0.02	0.00	['OBD']	3
Steel	0.33	0.00	0.00	2.42	0.00	0.07	0.71	['OBD']	19
Wood	0.29	0.04	0.00	0.72	0.00	0.69	0.34	['OBD']	10

Material	D_Mean	D_Median	D_Min	D_Max	D_Q1	D_Q3	D_Sd	D_DB	D_Count
Aluminium	-6.45	-6.50	-11.19	-3.09	-8.69	-3.63	2.56	['ICE' 'OBD']	24
Asphalt	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.00	['OBD']	5
Brick	-0.88	0.00	-6.12	0.00	-0.01	0.00	2.14	['OBD']	7
Cement									0
Concrete	-0.07	0.00	-2.68	0.00	-0.01	0.00	0.42	['OBD']	39
Glass/Glazing	-0.71	-0.06	-3.85	0.12	-0.16	0.05	1.45	['OBD']	22
Gypsum	-0.01	0.00	-0.20	0.00	0.00	0.00	0.04	['OBD']	21
Insulation	-0.98	-0.43	-21.30	0.00	-0.94	-0.04	2.98	['OBD']	49
Membrane	-1.35	-1.37	-2.16	-0.67	-1.62	-1.10	0.37	['OBD']	25
Paint	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	['OBD']	3
Steel	-95.18	-1.33	-1496.00	323.71	-1.46	-1.16	356.72	['ICE' 'OBD']	56
Wood	-0.55	-0.60	-1.18	-0.05	-0.79	-0.28	0.30	['OBD']	66

Appendix F – Interactive Data Visualization

More interactive data visualization can be found here: https://jsyc82.github.io/ThesisWeb/#27